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ABSTRACT

This study suggests and identifies computer image generation (CIG) algorithms for visual simulation that improve the training effectiveness of CIG simulators and identifies areas of basic research in visual perception that are significant for improving CIG technology. The first phase of the project entailed observing three existing CIG simulators. During the second phase, existing perceptual knowledge was studied in light of the capabilities and limitations of existing CIG simulators. The analysis resulted in a list of 12 perceptual limitations of these CIG simulators which include contrast management and aerial perspective, resolution dynamic range, directional illumination effects, raster effects, color, level of detail, surface definition, perceived flatness of the display, minimal scene content, size and continuity of the visual field, and hybrid display and update. In the third phase, improved CIG algorithms were developed in the areas of aliasing controls, scene, environment and sensor models, display properties, and future algorithms in high density of features and reflection models. Further research is recommended in seven areas of perceptual research and in five areas for algorithm research. A bibliography of 38 references and appendices containing consultant interviews and literature summaries are included. (CHC)

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AIR FORCE HUMAN RESOURCES LABORATORY

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ADVANCED COMPUTER IMAGE GENERATION TECHNIQUES EXPLOITING PERCEPTUAL CHARACTERISTICS

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The Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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PREFACE

This study was accomplished to suggest advanced computer image generation (CIG) techniques which will exploit the capabilities/limitations of the human visual perceptual processing system and improve the training effectiveness of visual simulation systems. The secondary objective of this effort is to identify areas of basic perceptual research that promise to have significant impact on future CIG technology. This report should be of value to anyone involved in real-time visual simulation using computer image generation.

This study was performed for the Air Force Human Resources Laboratory under contract F33615-78-C-0020. Mr. Michael Nicol was the contract monitor for the Air Force, and Mr. Anthony J. Stenger was the program manager for Technology Service Corporation. Dr. James P. Thomas of the University of California at Los Angeles and Dr. Myron Braunstein of the University of California at Irvine performed all the work in the perceptual area. Mr. Timothy A. Zimmerlin contributed the material on CIG algorithms and systems. Mr. Thomas Murray of the University of California at Los Angeles and Mr. Jack Schryver of the University of California at Irvine performed the literature search and prepared the summaries.

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1. INTRODUCTION

This final report documents a study that Technology Service Corporation (TSC) completed for the Air Force Human Resources Laboratory. The report is structured to parallel the progress of the individual project phases.

This first section introduces the project and provides a summary by discussing the project's objective, approach, results, and recommendations. The remaining sections present the findings of the project in greater detail. The information is intended for computer image generation (CIG) system designers, data base constructors, psychologists, and training personnel.

1.1 OBJECTIVES

The study objectives involve applying psychological knowledge of visual perception to improve real-time CIG simulators. The primary objective is to suggest and identify CIG algorithms for visual simulation that improve the training effectiveness of CIG simulators. The secondary objective is to identify areas of basic research in visual perception that are significant for improving CIG technology.

The objectives of the project have been met. A number of CIG algorithms are described in this report, most of which can be applied to existing simulators with only slight modifications to the simulators' basic designs. Some algorithms involve the scene and environment models and require no hardware modifications. A few algorithms impact the display requirements of future CIG simulators.

The algorithms were suggested by observing the perceptual limitations of existing CIG simulators. The perceptual objectives were further met by

1. Categorizing the perceptual limitations into common perceptual areas according to their underlying perceptual mechanisms and areas of future research for their potential solutions.
2. Identifying four primary and three secondary areas of perception that merit further research and experimentation because they show promise for understanding and alleviating the perceptual limitations.

1.2 APPROACH

The project proceeded in a sequence of three phases. The first phase entailed observing existing CIG simulators. During the second phase, existing perceptual knowledge was studied in light of the capabilities and limitations of existing CIG simulators. In the third phase, improved CIG algorithms were developed and relevant areas for further perceptual research were identified.

For the first phase, three major manufacturers of CIG simulators were visited on site. Two psychologists with extensive backgrounds in human visual perception, the TSC staff of CIG engineers, and the manufacturers' personnel discussed and viewed the simulators. The dialogue involved the designers and users of the simulators. Based on the observations and intensive interviews, a list of limitation areas was drafted.

The second phase involved both interviews with recognized experts in visual perception relating to flight training and an extensive literature search. This phase was tied to the limitation areas identified in the first phase. The limitations were researched in depth to verify their effects and psychological bases. The interviews and retrieved literature provided a base of knowledge for building improved algorithms and identifying needed research. Section 2 of this report describes Phases I and II and details the identified limitation areas. Summaries of the interviews and over 100 literature items appear in Appendixes A and B, respectively.

The third phase involved developing improved and new CIG algorithms. Based on TSC's insight into current CIG simulators, algorithms were developed to produce the appropriate display phenomena in a practical way. Based on perceptual knowledge, general performance goals and undesirable effects were defined. Some recommendations are based on tentative conclusions, and there is a need for further applied research. At issue are both the necessity for implementing some algorithms and the relative merits of alternative algorithms. The algorithms are presented in Section 3, and the areas of recommended research are described in Section 4.

1.3 RESULTS

An intensive analysis of existing CIG simulators, including those of the three major builders, defined 12 limitation areas:

1. Contrast Management and Aerial Perspective
2. Resolution
3. Dynamic Range
4. Directional Illumination Effects
5. Raster Effects
6. Color
7. Level of Detail
8. Surface Definition
9. Perceived Flatness of the Display
10. Minimal Scene Content
11. Size and Continuity of the Visual Field
12. Hybrid Display and Update.

While some limitations reside in the available hardware, others are in the basic approach. For example, contrast management and aerial perspective are serious limitations in existing simulators. No atmospheric attenuation and scattering model is used in the simulators except for bad weather conditions (e.g., fog, clouds), and the resulting perceptions are significantly degraded. As in some of the other limitation areas, several solutions are possible. These are addressed in Section 3 in terms of improved algorithms, but the available perceptual knowledge provided in Section 2 is needed to understand the full effect of and potential solutions for these limitations.

Many of the limitations are perceptually related and compound the effects of single limitation areas. For example, apparent size, depth, and motion are intrinsically related although not directly correlated to one another. Size, shape, and surface normal direction are also closely related. The limitation areas, singly and jointly, produce perceptual inaccuracies in the trainee's response. The findings reported in the literature help to identify both the interactions and the potential solutions or improvements.

Table 1 presents the major areas of improved algorithms as related to the limitation areas. These areas for improvement involve the basic algorithm, free design parameters that need to be optimized, and basic performance goals. The majority of the ideas need only simple modifications in order to be applicable to existing simulators. However, some of the objectives (basically in scene complexity and reflection modeling--e.g., shadows, specular) may be beyond the capability of current approaches. The basic polygon approach can definitely be improved. Also, there are limitations in the current display approaches (e.g., hybrid displays) that can be removed or mitigated.

The limitations of CIG simulators provide different focuses for evaluating perceptual knowledge and improved algorithms. This information can aid others that are interested in improving CIG technology. The perceptual knowledge in the interviews and literature provides insight for requirements and underlying perceptual phenomena. The improved algorithms provide approaches for resolving the limitations.

1.4 RECOMMENDATIONS

The most important purpose of this report is to identify ways to improve CIG simulators. One way to accomplish this is to have designers and users read this information and make concrete suggestions. Another way is to incorporate a moderate number of the ideas into future procurements as performance specifications. A third approach, which is most applicable to this program, is to research the improved techniques and underlying perceptions in order to judge effectiveness and relative merit. All three approaches should be pursued.

The specific research areas identified in Section 4 should be considered for immediate study. Since there are several somewhat related areas, the research should also consider their interaction. Relating the psychological and physiological understandings of perception to the study of tone application methods is a basic way to develop adequate visual perceptions in CIG simulators. At issue are both how the human visual system operates and how to build effective CIG simulators.

TABLE 1. LIST OF IMPROVED ALGORITHMS

Algorithms	Limitation Areas											
	1	2	3	4	5	6	7	8	9	10	11	12
• Aliasing Controls												
Gaussian impulse response		X	X		X		X					
Frame/field conditions		X			X							X
Hybrid picture effects		X										
• Scene and Environment Models												
Atmospheric attenuation and scattering	X	X	X			X	X	X		X		
Tone application methods				X				X		X		
Reflection models				X				X		X		
Level-of-detail controls	X		X				X	X		X		
• Display Properties												
Display face		X	X		X				X		X	
Contrast management	X	X	X									
• Future Algorithms												
High density of features				X			X	X		X		
Reflection models							X	X		X		

The areas recommended for further research from both perceptual and algorithm standpoints are listed in Table 2 and briefly described in the following paragraphs.

TABLE 2. AREAS FOR FURTHER RESEARCH

Perception-Based	Algorithm-Based
Aerial perspective	Smooth shading
Texture	Texture shading
Shadows	Shadows
Specular reflection	General reflection
	Contrast management

Although aerial perspective is widely accepted as a basic cue to relative distance, virtually no research has been performed to assess its actual importance. It is an obvious candidate for inclusion in CIG because it is easy to simulate. Thus, its true effectiveness should be investigated. An important question is whether aerial perspective interacts with and enhances the effect of texture.

There is little research on the effectiveness of texture in dynamic scenes. Also, the effectiveness of three-dimensional texture needs to be examined. Relative motion within the microstructure of the texture might be very important. As mentioned above, the interaction of texture and aerial perspective should also be investigated.

The shadows created by directional illumination are, in theory, a rich source of information to a moving observer. There is relative motion between the object and its shadow, and object and shadow undergo different shape transformations as the viewer moves. Since both of these factors are possible sources of information to the viewer, their actual importance needs to be established by research.

In theory, specular reflections can provide information about relative motion, surface definition and orientation, and relative distance. However, research is needed to establish their actual importance.

Gouraud (or smooth) shading is the common shading technique of current simulators. However, Gouraud shading results in an improper tonal perspective. The inverse-range shading technique recommended for development corrects this perceptual shortcoming.

The use of contrast management to maintain the display energy requirements within device limits has significant benefits. The experimental results, which indicate that differential filters reduce the energy output requirement for a given contrast perception, should be extended.

2. PERCEPTUAL LIMITATIONS OF EXISTING CIG SIMULATORS

The project was broken into two phases to investigate and determine possible solutions for the perceptual limitations of existing CIG simulators. During Phase I, a study of existing CIG simulators was conducted. Several visits were made to sites of current advanced systems, and designers and users of these systems were interviewed. Two psychologists used the data gathered from these activities along with their backgrounds in visual perception to identify 12 limitation areas:

1. Contrast Management and Aerial Perspective
2. Resolution
3. Dynamic Range
4. Directional Illumination Effects
5. Raster Effects
6. Color
7. Level of Detail
8. Surface Definition
9. Perceived Flatness of the Display
10. Minimal Scene Content
11. Size and Continuity of the Visual Field
12. Hybrid Display and Update.

Although these areas may overlap somewhat, they represent the complete spectrum of limitation areas in existing CIG simulators.

The purpose of Phase II was to consolidate and categorize current perceptual knowledge as it applies to CIG display problems/limitations identified in Phase I. The Phase II work was conducted in two parts: 1) the identified limitations were discussed with experts in the respective fields to identify areas of investigation and to propose possible solutions, and 2) a search of the available literature was conducted to identify potential information/mechanisms that might be exploited to solve each of the problem areas.

The investigations undertaken in Phase II are briefly described as follows.

Consultations with Experts. Consultants were interviewed at one aerospace company and four universities:

a. Conrad Kraft, Boeing Aerospace Company. (Several additional members of the Crew Systems Division participated in this interview.)

b. Herschel Leibowitz, Pennsylvania State University

c. Allen Pantle, Miami University

d. Tarow Indow, University of California, Irvine

e. Walter Gogel, University of California, Santa Barbara.

The general format of the interviews was as follows. Prior to the interview, each consultant was sent written materials on the purpose of the study and on the limitations observed during Phase I. These materials included the statement of work for the program and the trip reports from visits to assess various displays. The latter included not only descriptions of the limitations observed, but also tentative analyses of the psychophysical processes involved. During each interview, the consultant was queried about the limitations relevant to his expertise in order to develop and refine the psychophysical analysis and to identify relevant literature sources. The interviews were sufficiently open-ended and the consultants sufficiently experienced and knowledgeable that information about additional limitations was volunteered and alternative psychophysical analyses proposed.

TSC used the results of the interviews to prepare the descriptions of observed limitations and the psychophysical analyses of these limitations, to select the literature to be reviewed, and to formulate the recommendations. Detailed summaries of the interviews are given in the individual reports provided in Appendix A.

Literature Summaries. More than 100 articles were reviewed during the literature search portion of the investigation. Each resulting summary comprises a separate review of the document/article, a discussion of its relevance to the specific limitation, and its implication as a solution to the limitation. The literature summaries are in Appendix B, arranged according to the 12 limitation areas.

The following subsections discuss the 12 limitation areas defined by Phase I. Each limitation area provides a perceptually concrete and coherent focus for further work. Thus, while some areas are related, each is resolved independently in order to focus on the basic perceptual limitation. In addition, the material presented makes use of the knowledge gained through the literature search of Phase II. That is, information from the Phase II investigation that concerns psychological bases for the limitation areas, areas of perceptual research, and possible solutions has been incorporated into the discussion.

2.1 CONTRAST MANAGEMENT AND AERIAL PERSPECTIVE

Several different problems can be grouped together because a combination of contrast management and aerial perspective can be used to mitigate them. Contrast management refers to controlling the appearance of an object by manipulating its physical contrast. A certain amount of this manipulation can be accomplished in the model or data base. Other manipulations require real-time computation and can be accomplished by introducing aerial perspective. Aerial perspective is advantageous in that it makes its own direct contributions to realism and perceptual validity as well as contributing to contrast management.

Aerial perspective refers to changes in contrast and hue which are normally produced by the atmosphere. The light which a viewer receives from a distant object is altered in two ways: 1) a portion of it is absorbed by the atmosphere, and 2) a portion of it is scattered. The scattering reduces the light signal from the distant object and also creates a veiling illumination that reduces contrast and saturation. Both forms of alteration are wavelength-selective and their magnitudes increase with viewing distance. Thus, an object's contrast, hue, and saturation are altered as a function of viewing distance. These shifts are commonly recognized as cues to distance perception.

One problem in this group involves point light sources which recede into the distance. The lights edging a runway provide a prime example in that beyond a certain distance they appear to grow larger and brighter with increasing distance. Or, alternatively, they appear to rise vertically rather than recede into the distance, thus causing the runway to "stand up." It must be noted that runways tend to "stand up" at night under natural viewing conditions, as they do in the simulator. Similar problems occur whenever there is a string of uniformly spaced lights of equal size and intensity, such as street lights. The problem is exaggerated by the simulator, and stems partly from the limited resolution of most displays and partly from the absence of simulated aerial perspective.

Ignoring atmospheric effects, the light entering the eye from a source of restricted size decreases as the square of the viewing distance. However, within certain limits, the area of the retinal image also decreases as the square of the viewing distance. Thus, with these limits, the illuminance of the retinal image (ratio of flux to area) remains constant. The limit is approached as the angular subtense of the light source approaches the resolution limit of the eye. As viewing distance increases further, and the angular subtense of the source goes below the resolution limit, the retinal image remains essentially constant in size. However, the illuminance of the image now decreases as the square of the viewing distance. The source becomes invisible when the illuminance drops below the detection threshold.

In the simulator, the video image of the light source is decreased in area as the square of the calculated viewing distance, thus producing naturalistic changes in retinal image size. However, the video image cannot be reduced below one pixel. For most displays, one pixel subtends an angle two to four times larger than the optimal resolution limit. Thus, the visual system may "expect" further increases in viewing distance to be accompanied by further reductions in retinal image size. However, because the display cannot produce smaller images, perceptual distortion occurs. One approach to this problem stems from the fact that the resolution limit of the visual system depends in part upon the contrast or intensity of the objects viewed. By keeping the contrast between the light source and its surround low, the resolution limit of the visual system can be made to more closely approximate the display's resolution limit.

Another need is to reduce the luminance of the video image as the square of the calculated viewing distance once the one-pixel limit has been reached. If aerial perspective is simulated, the attenuation which it incorporates may serve the present purpose as well.

The relevant psychophysical literature concerns visibility and brightness as a function of stimulus size and shape; contrast sensitivity as a function of size, shape, and spatial frequency; and the optical-neural spread functions of the visual system.

Introducing aerial perspective may also help to correct the perceptual distortions involving receding light sources. By decreasing contrast (intensity) and saturation and shifting hue as a function of distance, the perception of lights as receding into the distance (rather than standing up) should be reinforced.

A related problem concerns a single object moving toward or away from the viewer, such as another aircraft or a building or vehicle on the ground. The problem is most noticeable when another aircraft is seen against the sky. Beyond a certain distance, the object is either perceived as motionless or as moving and changing in size. Again, the problem is that beyond a certain distance the size of the video image remains constant at one pixel and cannot be changed as a function of calculated viewing distance. With size fixed, the object is perceived as motionless or, alternatively, as simultaneously changing in size and distance. If the object is oblong, it may be perceived as changing shape or attitude. Again, two steps are in order. The first is to set the contrast of the object low so that the high spatial frequency components which distinguish one small image from another will be below the visual threshold (i.e., reduce visual acuity to match the resolution limit of the display). The second step is to vary the contrast of the object as a function of distance, which may be accomplished by simulating aerial perspective.

A third problem involves level-of-detail switching. Scene complexity is generally limited by omitting many features from the scene until the viewer comes within a certain distance of them. When the viewing distance is reduced to the critical value, the feature is switched in and generally appears abruptly on the screen. The sudden appearance is distracting and introduces an artificial cue to distance which is not present in actual flight. Again, there is a two-step procedure to lessen the problem: 1) make the contrast of the video image a decreasing function of calculated viewing distance, and 2) set the contrast of the object in the data base so that the object will be just at or below the threshold of visibility when it is switched into the scene. In other words, when building the data base, the designer should not ask, What is the contrast of this object in real life? The questions should be 1) At what viewing distance will this object be switched in? and 2) Given both the algorithm used to attenuate contrast as a function of distance and the contrast sensitivity of the visual system, what base contrast will put this object at the threshold of visibility when it is switched in? The relevant psychophysical literature concerns contrast threshold as a function of the size and shape of the object viewed.

The final problem in this group involves aliasing. Many objects scintillate at a particular distance because of interaction with the sampling and raster structures. The problem occurs only when the geometrical projection of the object onto the image plane is small relative to the period of the sampling and raster structure. It is almost invariable that the object in question is at some distance from the viewer. Again, the same two-step procedure may be applied: 1) make image contrast a decreasing function of viewing distance (as aerial perspective would do), and 2) set the base contrast of the object so that the object does not become visible until its video image is large enough to avoid aliasing problems.

None of the examined displays incorporated aerial perspective, although the "weather" algorithm which they all use can provide an approximation. Indeed, many users commented that introducing a small amount of weather greatly increased the display's realism.

As noted before, aerial perspective consists of variations in hue, saturation, and contrast as a function of viewing distance. These variations are commonly considered to be one of the many types of information used to judge distance. However, the relationship between these variations in perceptual qualities and viewing distance is not fixed--it changes with atmospheric conditions. Thus, aerial perspective is not a reliable cue to absolute distance (as a city-dweller quickly finds out when attempting to judge the distance of a remote peak in the more rarified and cleaner air of the mountains or desert). However, the role of aerial perspective in defining relative distances and surface orientations is not so highly dependent upon atmospheric conditions.

The absence of aerial perspective in a visual display contributes to the cartoonlike character and ambiguity of surfaces. In natural viewing, hue changes, saturation, and contrast decrease as a function of distance. Thus, a horizontal surface such as the earth continuously changes in hue and saturation as it recedes into the distance and the boundaries between one area and another become less and less distinct. A nonhorizontal surface such as the side of a mountain is immediately perceived as such because its hue and saturation are relatively constant and the boundary between it and other areas changes little in clarity. When aerial perspective is lacking in the simulator, these cues are absent and the viewer must "figure out" whether what is seen is the side of a mountain or an oddly shaped farm field. The problem is particularly noticeable in low altitude flight involving high-speed turns, banks, and rolls. In normal vision, pilots are aided in maintaining their sense of orientation because they instantly recognize surfaces and surface orientations. In the simulator, much of the information is missing, recognition takes longer, and a pilot may become disoriented.

Whereas the weather algorithms presently used produce changes in saturation and contrast as a function of distance, they do not produce changes in hue. In addition, because they were developed to simulate conditions in which visibility is substantially reduced, they may not provide an optimal approximation to the effects of aerial perspective under less restricted conditions of visibility. However, the weather algorithms can perhaps be modified to provide the desired hue shifts and a better approximation to the effects of aerial perspective under conditions of good visibility.

Two general comments can be made about aerial perspective. First, it provides much the same information as static, two-dimensional texture patterns, but at a lower cost. However, no research has been conducted to determine whether dynamic texture gradients are perceptually more effective (e.g., in removing ambiguities of surface definition) than aerial perspective gradients. Second, full simulation of aerial perspective requires the use of color displays, since variations in hue and saturation are involved. Thus, if introduced, aerial perspective would help to justify the greater expense of color displays.

2.2 RESOLUTION

The displays examined were limited in resolution relative to the acuity of foveal vision. In all cases, the limitation reflects a considered compromise between resolution and field of view. By reducing the field of view, it would be possible to match the resolution of the display to that of the human visual system. However, this course of action is generally not acceptable because of the judged importance of maintaining a normal field of view.

The impact of limited resolution can be discussed under three headings. Two of these concern types of perceptual tasks the pilot must perform: 1) detection and identification and 2) judgments of position, orientation, and size. The third category is the more global one of apparent realism.

2.2.1 Detection and Identification

Psychophysical research has established that an object or pattern first becomes detectable when the most visible Fourier component attains threshold contrast, i.e., when the component becomes visible in and of itself (although it will not necessarily be consciously perceived as such). In other words, to produce normal detection performance it is necessary to reproduce only the most visible components. For single objects and targets, the most visible components generally lie within 3 to 6 cycles per degree, a range that can be reproduced by current display technology. Thus, normal detection of single objects and targets is possible, although intelligent contrast management is required. Repetitive or periodic patterns are a different matter. The most visible component is usually the fundamental frequency component, which may lie outside the display's resolution range. Thus, repetitive patterns may not be resolved at their normal distances. Although there is no solution to this problem, data-base designers should be aware of the problem and know which patterns cannot be resolved by the display until the viewing distance is shorter than that at which visual resolution normally occurs. In addition to knowing the properties of the display, the designers need to know the normal resolution properties of the human visual system, i.e., contrast sensitivity as a function of spatial frequency and orientation.

The limited resolution of the display has a more profound effect upon the identification of distant objects, such as other aircraft or land-based vehicles or structures. Ginsberg (1978) likened such identification tasks to reading the letters on a Snellen acuity chart. He calculated that the spatial frequencies used to identify the smallest readable letters lie between 20 and 30 cycles per degree. Because such Fourier components lie well beyond the resolution range of the visual displays of most simulators, these displays cannot be used to simulate or train the identification of distant objects. However, CIG displays can be used for identification training if resolution is increased by reducing the field of view.

2.2.2 Judgments of Position, Size, and Orientation

Under optimal conditions, the human observer can discriminate changes in spatial position of only a few seconds of visual angle. Changes in size of less than 1 minute of visual angle can be detected, as can changes in orientation of less than 1 degree. These detectable changes involve movements of edges or contours which are small compared to the dimensions of a single pixel. For example, the misalignment of two vertical contours need exceed only a few seconds of arc in order to be perceived, whereas a single pixel is on the order of 3 to 6 minutes of visual angle wide. This fact might be taken to mean that this visual task cannot be performed with normal accuracy in the simulator. This fact also explains the observation that, in some of the CIG displays examined, edges were observed to change position or orientation and objects were observed to change size in perceptible increments or jumps rather than continuously. However, available psychophysical research suggests that by using appropriate image-forming algorithms, normal changes in size, orientation, and position can be simulated and approximately normal perceptual performance with respect to these changes can also be obtained.

It is useful to start by noting that the receptors of the eye, i.e., the "pixels" of the eye, are 20 seconds or more in width and are thus large compared to the smallest perceptible misalignment. A shift in the position of an edge, even if it is only a few seconds of visual angle, can be detected because the edge is represented on the retina not by a step function, but by a gradient of illumination extending over many receptors. This gradient is the convolution of the edge with the optical spread function of the eye. Because of this transformation, changes in the spatial position of the edge are coded as changes in the ratio of illumination falling on adjacent receptors. Given a good signal-to-noise ratio within the receptors (produced by a high contrast edge), a change in position can be detected which is small relative to the spacing of the receptors or sampling elements. The same principle can be extended to the level of the display. By convoluting the edge with a "blurring" function, the edge can be represented by a gradient extending over several pixels. Changes in the position of the edge are represented by changes in the ratio of intensities of adjacent pixels. Research by Westheimer and Hauske (1975) on "hyperacuity" indicates that the human observer extracts position information from such gradients with an accuracy that is comparable to that obtained when the external stimulus is a step function. In other words, the visual system extracts position information from gradients as well as from step edges. (Because of signal-to-noise considerations, accuracy in localizing the step must be somewhat better than in localizing the gradient.) Research by Thomas and Kerr (e.g., 1969) indicates that the perception of size is relatively unaffected by whether edges are represented by steps or gradients.

In summary, changes in position, size, and orientation that are small compared to a pixel can be represented in the display by convoluting the image with a blurring function. Psychophysical research indicates that human observers can extract information about position and size from this type of representation.

2.2.3 Realism

Limitations in resolution reduce the realism of a CIG display, particularly when distant objects are represented. In the Fourier domain, a single distant object is represented by a broad spectrum of spatial frequency components. The typical CIG display reproduces only the lower part of this spectrum. If the contrast of the object is high enough and the magnitude of the reproduced components great enough, the visual system "expects" to see the rest of the spectrum and interprets its absence as a lack of realism. On the other hand, if the contrast of the object is low, the magnitudes of all the components will be reduced and the visual system will not expect to see the high frequency components because of the low contrast and the reduced sensitivity of the visual system to high spatial frequencies. In other words, the visual system attributes the failure to detect high frequency components to its own insensitivity rather than to a lack of realism in the display. Thus, the realism of the display can be increased by appropriate contrast management. It should be noted that such management in no way increases the amount of information contained in the display. However, it might improve training effectiveness by improving user acceptance.

The relevant psychophysical research areas are detection and identification, particularly with respect to the spatial frequency components used for each type of task. Hyperacuity and the effects of blur on hyperacuity judgments are also relevant. Contrast sensitivity as a function of spatial frequency is relevant to contrast management for increasing realism.

2.3 DYNAMIC RANGE

The range of light intensities in the natural world is orders of magnitude greater than that of any existing or forseeable CIG system. The limited dynamic range of the CIG system manifests itself in several ways. Point sources of light cannot be represented with enough intensity to have the same visibility or apparent brightness that they have in the real world (strobe lights are a common example of this problem). Another problem concerns the visibility and apparent contrast of objects seen against different backgrounds at different times. In the real world, the visibility and contrast of an object change drastically from one background condition to another. For example, a light-colored aircraft that is illuminated by the sun and seen against a shadowed, dark hillside appears bright, almost luminous, and is easily seen. A few seconds later, the same aircraft is seen against a bright sky and is perceived as a low-contrast, barely detectable object. Under some conditions, the aircraft is perceived as a dark object when silhouetted against a bright sky. These changes in visibility and apparent contrast result from the large range of background and illumination conditions in the real world. Such changes are rarely seen in simulator displays because the displays have limited dynamic range.

Most simulators omit the windscreen because it would reduce the already limited brightness of the visual display. However, the windscreen is the source of several types of visual distortions, and the problems posed by these distortions are removed from the training situation when the windscreen is absent. Some of the distortions are prismatic in character and result from curvatures and nonuniformities in the windscreen. Other problems arise from dirt, scratches, insects, etc., on the windscreen. These visual objects provide stimuli for inappropriate (close) accommodation, and may also be perceptually projected against the distant sky and momentarily interpreted as other aircraft. Another source of impairment is that the multiple layers of the windscreen scatter light and degrade the physical image formed on the viewer's retina. The problems posed by scattered light increase in severity as the dynamic range of the visual scene increases. Thus, these particular problems would not be duplicated in the simulator even if the windscreen were built in.

The limited dynamic range also contributes to lack of realism in the visual scene and tends to give a cartoonlike character. The limited realism is most noticeable at low altitudes and/or low sun angles.

2.3.1 Remedial Steps

Some steps can be taken to mitigate the problems posed by limited dynamic range. Although the human visual system functions over a wide range of light levels, it has a limited response or output range. Thus, compression of the dynamic range is part of the normal visual process. In part, normal compression is carried out by changing the gain of the visual system through processes of adaptation. In addition, the visual system also tends to differentiate the visual scene, i.e., tends to be more sensitive to spatial and temporal changes than to absolute levels of stimulation. Because of this latter property, the dynamic range of a display can be reduced without causing significant perceptual effect, provided that the spatial and temporal changes are not reduced. In other words, appropriate high-pass spatial and temporal filtering can reduce the display's dynamic range with only a minimally perceived effect.

The following basic strategy is suggested: the data base or model should approximate the dynamic range of the real world. To do so, three steps should be incorporated in the image generation process. The first step is an algorithm that simulates the light scattering properties of a windscreen (if inclusion of these effects in the training situation is desired). The second step is appropriate band-pass spatiotemporal filtering to reduce the dynamic range requirements. Design of this filtering process should be based upon the spatiotemporal impulse response and contrast sensitivity functions of the human visual system. It should also take into account light scattering within the display faceplate and optics. The final step is to apply a compressive transformation to reduce the dynamic range of the filtered image so that it will match the range of the display device. This compression function should reflect the results of both psychophysical studies that have scaled subjective brightness and contrast and physiological studies of response compression within visual receptors.

2.3.2 Relevant Literature

The relevant literature concerns the spatiotemporal impulse response function of the visual system, including studies of spatial and temporal summation and spatial and temporal inhibitory interaction. Studies of the visual system's contrast sensitivity as a function of spatial and temporal frequency present this information in a different but still useful form. Cornsweet (1970) discusses illusions designed by him, O'Brien, and Craik that provide relevant examples of filtered or differentiated displays. Relevant examples were also included in some of Land's papers (e.g., Land and McCann, 1971) on the Retinex model. The visual "missing fundamental" is also relevant (e.g., Furchner, Thomas, and Campbell, 1977). Scaling studies of the power-law relationship between physical intensity and perceived brightness or between physical and perceived contrast are relevant to design of the compression function. However, the best function is probably an adaptation of the one used by physiologists to describe response compression at the receptor level. The function and its relevance to psychophysics are described by Hood, et al. (1978).

2.4 DIRECTIONAL ILLUMINATION EFFECTS

Directional illumination, i.e., incorporating the sun into the data base as the source of illumination, has several perceptual consequences. One is the shadows cast by trees, buildings, vehicles, etc. These shadows contribute to the "vertical development" of the scene; they help to define surfaces and the relationship between an object and the surface on which it sits. In dynamic scenes, the relative motion between object and shadow helps to define the spatial position of the object. Only one of the displays examined incorporated shadows. The absence of shadows detracts from realism and contributes to the ambiguity of surfaces and distances.

Specular reflections are another consequence of directional illumination. Although it is theorized that these reflections can provide the viewer with information about rates of motion, distances, and the orientation of surfaces, there is no body of psychophysical evidence on the extent to which human observers can actually use such information. On the other hand, it is established that specular reflections desaturate colors and cause highlights. None of the displays examined simulated specular reflections. The absence of these reflections undoubtedly contributes to the unnatural-looking colors in CIG displays and may contribute to the fact that surfaces often lack the character of surfaces or surface mode.

Finally, the lack of directional illumination eliminates various effects of sun glare. The task of detecting and recognizing another aircraft is much more difficult when that aircraft approaches from the direction of the sun. Thus, sun glare produces significant problems that it may be desirable to include in some training situations. Because of the limited dynamic range of CIG displays, special algorithms are probably necessary to effectively simulate glare. In terms of the three-stage process suggested in Subsection 2.3.1, the glare algorithm would be placed in the first stage. Two types of information should be incorporated in the algorithm: 1) physical scattering of sunlight by the atmosphere and windscreen, which partly produces a veiling illumination that reduces the target's effective contrast, and 2) a bright object's perceptual masking effects on the detection and recognition of dimmer nearby objects. This perceptual effect is over and above the physical effects of scattered light. The relevant literature is under the topics of glare and brightness contrast. Some of the relevant works are by Fry and Alpern (1953), Diamond (1955,1962), and Owens and Leibowitz (1976).

2.5 RASTER EFFECTS

In the displays examined, the CRT was magnified to the point that the raster structure (scan lines or dot matrix) was resolvable. The presence of a perceivable raster structure has several undesirable effects. First, the structure tends to mask or prevent the detection of small objects or fine patterns. It must be emphasized that this perceptual problem is in addition to the purely physical sampling and aliasing problems that arise when an object's dimensions approach those of the raster elements. The severity of the masking effects, which is directly related to the contrast of the raster structure, can be reduced by demodulating the raster. Although such demodulation may not be feasible for displays in which the raster elements are defined by a shadow mask, it can be effected in other displays by blurring the electron beam.

Another undesirable effect of a visible raster is that it tends to define the face of the CRT as a single surface, orthogonal to the line of sight. Thus, it works against the goal of the CIG display to create the illusion of a three-dimensional scene. Even when the illusion is not destroyed, the existence of the flat raster structure causes distances to be underestimated. One symptom of this underestimation is that distant stationary objects may be perceived as moving with the observer. Such false movement was perceived in the Williams Air Force Base display that has prominent raster lines. With respect to this particular misperception, the relevant literature is by Gogel (1976) and concerns apparent motion as a measure of perceived distance.

Finally, a resolvable raster provides a strong stimulus for accommodation. Owens (1976) showed that the middle spatial frequencies (between about 3 and 8 cycles per degree) are the most effective in stimulating accommodation. The fundamental frequency of most rasters lies within this range. Because the display optics place the raster at optical infinity, the raster stimulates accommodation toward infinity, which is appropriate and desirable for out-the-window viewing. The potential problem is that this stimulation is absent from normal flight conditions. Out-the-window viewing normally does not provide adequate stimulation for far accommodation. Thus, one set of problems which pilots normally face arises because their accommodation is often inappropriate for detecting and recognizing distant objects. This set of problems is removed from the training situation when the raster provides cues to distant accommodation.

2.6 COLOR

The color of CIG displays is widely described as too vivid and cartoonlike. Target objects often stand out excessively because of coloration and thus are too easily detected. In addition, data base compilers often complain about the difficulty of selecting acceptable colors for objects.

These problems can be related to a set of common causes. In the natural world, aerial perspective and specular reflection combine to reduce saturation. Further, because of the joint action of directional illumination and specular reflection, few surfaces appear uniform in color when closely examined. Rather, there is variation in lightness and saturation (and sometimes hue) even across flat surfaces. In the case of surfaces extending into the distance, aerial perspective also contributes to the variation in color. When aerial perspective, specular reflection, and directional illumination are not simulated, colors are too highly saturated and too uniform. One result is the cartoonlike appearance. Another is that targets are too visible, although this problem also stems from a lack of background clutter.

One remedy is to incorporate aerial perspective, specular reflection, and directional illumination into the simulation process. A less effective way is to approximate the results of the processes by manipulating the data base. Specifically, the saturation of objects can be reduced, the hue can be shifted toward that of the illuminant, and surfaces can be graded from one part to another with respect to lightness, saturation, and hue. Although these changes would probably increase realism, they would convey only limited information to the viewer because they do not change as a function of the viewer's position in space.

2.7 LEVEL OF DETAIL

Two problems were observed with respect to level-of-detail switching. One is that an object does not move smoothly in and out of the field of view; instead, it abruptly pops out of view as soon as any part of it reaches the edge of the field. Or, conversely, an object pops into view only when the entire object is within the field of view. Second, an object suddenly pops into or out of view as its distance from the viewer becomes less or exceeds a critical value.

Both of these effects provide artificial information that can contribute to negative transfer. The abrupt insertion or removal of an object may make the object more noticeable and more detectable than is normally the case. Also, switching objects in or out of the scene at a particular viewing distance provides an artificial cue to distance.

To solve the first problem, an algorithm is required that will permit objects to move smoothly in and out of the field of view, i.e., an algorithm in which the object is not removed entirely from the scene as soon as any part of it passes out of the field of view. The second problem can be mitigated by contrast management (see Subsection 2.1).

2.8 SURFACE DEFINITION

A number of related problems were observed in regard to surface definition in CIG displays. Surface orientations with respect to the observer or to other surfaces were often ambiguous, as were the apparent distances and sizes of surfaces. Some of these ambiguities exist in direct vision, but the general ambiguity of surface definition appeared to be greater in CIG displays, and some specific difficulties appeared to be characteristic of these displays.

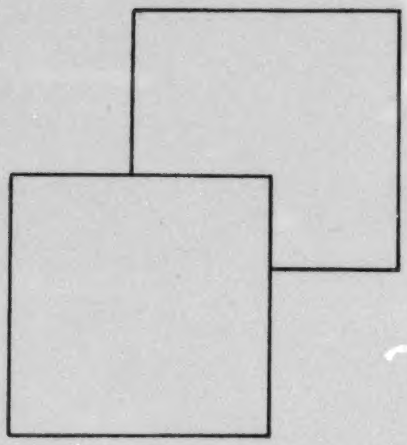
In direct vision the perception of surfaces is usually based on several sources of redundant information. Most surfaces have visible textures that help define them as surfaces and may also provide gradients that indicate surface slant. Surfaces exhibit brightness gradients as a result of variations in orientation to a light source, and they exhibit brightness, saturation and hue gradients as a result of atmospheric attenuation (see Subsection 2.1). Surfaces may reflect light sources or other surfaces, and most surfaces have irregularities that produce shadows. In addition, a surface may be covered with features that cast shadows (e.g., trees), and one surface may cast shadows on another.

In current CIG displays, almost all of this surface definition information is absent. Surfaces are defined by simple polygons that differ in hue. This method of defining surfaces produces ambiguities because it eliminates redundant information that is usually available in direct vision, and also produces specific misperceptions associated with displays consisting of simple polygons. The following specific problems were observed.

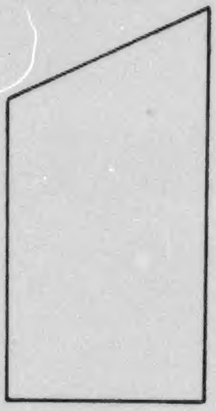
A hill depicted as a set of adjacent polygons appeared flat unless it intersected the horizon. In the absence of cast shadows, texture gradients, brightness gradients, and aerial perspective, the sides of hills usually appeared to be flat areas on the surface. The intended shape was revealed only after introducing contour interruption as a hill intersected the horizon. This difficulty in perceiving the orientation of sloping terrain from an overhead viewpoint is not characteristic of direct vision.

Surface elevation was sometimes perceived when it was not present in the model. This mistake was due to the presence of misleading information that was probably more effective in determining surface perception than it would have been if more information about the intended distances and orientation of surfaces had been present. Dark areas adjacent to surfaces appeared to be shadows; thus, the surfaces were perceived as elevated above the ground plane (a misperception that can also occur in direct vision). Highly saturated colors appeared to be either elevated or depressed to observers as a result of chromostereopsis--an unlikely occurrence in direct vision because the requisite saturations would not exist.

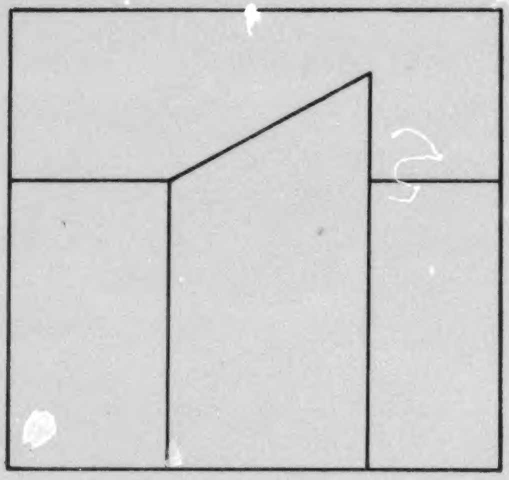
Illusions of surface slant occurred as a result of certain shapes and combinations of polygons. The use of an acute and an obtuse angle in adjacent corners may lead to perceiving the included side as slanted with respect to the line of sight. Contour interruption may imply depth separation. These two effects can work separately, but are especially effective in combination, as shown in Figure 1. These effects appear to be more frequent in CIG displays than in direct vision and could be in



Interposition



Oblique Contour Angles



Combined Interposition and Oblique Contour Angles

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Figure 1. Perceptual Illusions

part corrected through attention to the shapes and intersections of polygons in the model.

The sizes of objects, such as buildings, were sometimes ambiguous. This partly resulted from the ambiguity of distances, but in some situations the ambiguity of sizes was even more noticeable. Although there is a close relationship between size and distance perception, perceived size does not always depend on perceived distance. Perceived size may even determine perceived distance when other distance indicators are absent. The degree to which familiar size is important in distance perception is a subject of some disagreement, but in general the use of objects of known size whenever possible would appear to be a good strategy for the model builder.

A final example of a problem in surface definition is the occasional appearance of a surface area as an area of detached color rather than as a surface. This is referred to as the aperture mode of appearance because it occurs when an area of uniform color is viewed through an aperture. This mode of appearance can also occur without an aperture if cues to distance and other information that usually defines a surface are absent or reduced. The absence of microstructure or texture, specular reflections, and shading in CIG displays may contribute to the aperture mode of appearance.

Overall, the problems in surface definition appear to be the result of both missing and misleading information. Although cost considerations would prevent adding all missing information, it may be possible to add the information that is most important to surface definition. Some indication of which information is most important can be gleaned from existing literature, but specific investigations in the CIG context will probably be necessary. The elimination of misleading information, on the other hand, should not be difficult.

Because the display is presented on a flat surface, only the so-called pictorial cues to depth are present. Binocular disparity, accommodation, and convergence are not available to assist in surface definition. The literature on depth perception in static displays

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indicates that these three sources of information would not be useful for surface definition at the distances that are simulated in CIG displays. However, a recent study with a dynamic display (Beverly and Regan, 1979) suggests that observers are more sensitive to binocular disparity that is changing continuously as a result of the observer's motion toward or away from a scene than they are to static disparity. Although disparity may play a role in surface definition in direct vision, cost considerations would probably prevent its use in CIG displays, and its value at the distances simulated in these displays remains uncertain.

Among the pictorial cues, texture is noticeably absent in current CIG displays. Real-world surfaces almost always display a texture based on intrinsic variations in the surface (microstructure) and/or superimposed elements (grass, trees, etc.). The value of texture in solving problems of ambiguous surface distance or elevation is questionable, and there is evidence that static texture gradients are not useful in defining surface orientation unless the texture is regular. Texture may be of value in reducing the occurrence of the aperture mode of surface appearance. The major value of texture in surface definition would be as a carrier of velocity gradient information. The orientation of a surface can be perceived on the basis of the relative velocities of the texture elements as the observer moves past the surface. Observers may also use the velocity of the texture elements in judging their velocity with respect to the surface. The role of element size and familiarity or recognizability in such judgments is uncertain.

A second noticeably absent pictorial cue is shadow. The role of shadow in surface perception is easily demonstrated: turning a photograph upside down can cause indentations to appear to be protrusions. Realistic shadows would aid accurate perception of hillsides, and their presence in a scene might reduce false elevation perceptions because there would be no shadows around a surface that is not elevated. In addition to shadow per se, surface definition would also be aided by the presence of brightness gradients resulting from the orientation of surfaces to the light source.

Aerial perspective produces brightness, hue, and saturation gradients that should be useful in defining the relative distances of surfaces. (This cue was discussed in Subsection 2.1.)

Misleading information about surface orientation and elevation was produced by the use of simple polygons with certain combinations of oblique contour angles, intersecting contours that falsely indicated overlap of adjacent surfaces, highly saturated colors that are subject to chromostereopsis, and dark areas that falsely suggest shadows. These sources of misleading information should not be difficult to eliminate.

2.9 PERCEIVED FLATNESS OF THE DISPLAY

The preceding subsections discussed several types of information that might enhance the intended perceptions of surface distance, orientation and size in CIG displays (e.g., aerial perspective, shadow, texture gradients). The types of information in current CIG displays that interfere with these intended perceptions by revealing the flatness of the display are binocular viewing without disparity, visible monitor frames, and a visible raster pattern.

Binocular viewing reveals the flatness of CIG displays because the lack of disparity indicates that all points on the display are equally distant from the observer. There is no practical solution to this problem: displays with correct disparity would be costly and present new technical difficulties, and limiting the trainee to monocular viewing would reduce the field of view and be a generally unrealistic solution.

The presence of visible frames around the monitors is another important indicator of the display's flatness. (Perceived depth in a home television set can be enhanced by looking through a tube that limits the field of view to the picture itself and thus eliminates the visible frame.) The elimination of visible monitor frames should be a consideration in the design of CIG displays.

A regular two-dimensional pattern superimposed on a simulated three-dimensional scene increases the perceived flatness of the scene. This is one of several reasons for reducing the visibility of the raster pattern (see Subsection 2.5). A visible raster pattern interferes with the perception of the scene as three-dimensional.

A simple binary decision does not determine whether a display appears to be either flat and in the plane of the monitor screen or three-dimensional. There is usually a compromise between these two extreme perceptions, and where this compromise lies on the flatness-to-depth continuum determines the perception of sizes, slants, distances and velocities in the display. The greater the tendency to perceive the display as flat, the more objects will appear to have the sizes and shapes projected on the screen rather than those intended in the three-dimensional scene. Consider, for example, a runway that projects a trapezoidal shape on the monitor. The perception of the runway may vary from a rectangle at a slant to a trapezoid in the plane of the monitor screen, depending in part on the perceived flatness of the display. Any increase in perceived flatness will tend to make the runway appear less slanted and more trapezoidal, thus interfering with the intended perception of the runway's slant and shape in three-dimensional space.

There is very little literature on "cues to flatness." A relevant topic would be the relative influence of flatness and depth cues on shape, slant, size, and motion perception, including size, shape and speed constancy, and shape-slant invariance.

2.10 MINIMAL SCENE CONTENT

Current CIG systems display less than 5 percent of the edges that would appear in a television picture of an average-day scene taken with a camera. This figure is based on counts (reported by Boeing staff members) of 30,000 to 500,000 edges in a television picture, with an average of 100,000. This figure can be compared to current CIG capabilities that usually run well under 5,000 edges. The edge count in direct vision would be considerably greater than the 100,000 figure, which is limited by the low resolution of television pictures.

The use of displays that provide an extremely small percentage of the scene content available in direct vision has several effects. First, the perceived realism of the display is reduced. The implications of reduced realism for transfer of training will depend on the training objectives and the experience of the trainees. For some combinations of objectives and trainee experience, perceived realism may not be important as long as the critical cues for the task are present in the display. Under other circumstances, lack of realism may reduce the trainee's acceptance of the simulation and thus have a detrimental effect on achieving the training objectives. The relevant literature would be in the training area rather than in the perception area. Studies concerned with the effects of visual realism on transfer of training or on display acceptance would be useful, especially if training objectives or trainee experience is varied.

A second effect of minimal scene content is that training may not be possible in tasks requiring detection of an object in a cluttered environment. There are two ways to realistically simulate the clutter that would be present in the real-world scene. The first of these is to introduce artificial clutter in order to provide the level of difficulty required for the detection task, and thus avoid the computational load that would be associated with a comparable increase in realistic scene content. However, if artificial clutter were used in place of realistic scene content, its effects on transfer of training in detection, recognition, and identification tasks would have to be considered. Any regularity in the artificial clutter patterns that did not occur in the real-world scene might adversely affect transfer of training.

The other approach to a realistic clutter simulation would be to provide the clutter needed for detection tasks only in the part of the scene that is within a specified distance (in visual angle) from the observer's momentary fixation point. To do this would require a continuous monitoring of direction of gaze. The feasibility of this approach depends on the speed and magnitude of eye movements that may occur in the training situation and on the effects of reducing detail in the periphery--information which should be available in the existing literature. Methods to reduce detail in the periphery without causing distraction would have to be considered. This consideration would involve the observer's sensitivity to various changes in the periphery (e.g., changes in spatial frequencies) that might be affected by a reduced level of detail.

A third effect of minimal scene content is a possible reduction in the impression of self-motion and in the accuracy of judging the speed of self-motion. A display may not have a sufficient number of edges to produce an impression of self-motion appropriate to the simulated conditions. Velocity judgments may not correspond to judgments in direct vision if the frequency of edges or texture density is reduced. More realistic impressions of self-motion might be obtained by adding more edges, but an accurate simulation of edges in the environment may not be required. Less costly alternatives that have been considered include the use of symbolic patterns at critical locations in the scene (e.g., on runways) as a substitute for the surface irregularities present in direct vision, and the use of texture tiles of varying densities that approximate the densities of natural textures (grass, trees, etc.) to cover surface areas. The relevant research area concerns how variations in texture density and recognizability of texture elements affect perceived self-motion and the accuracy of velocity judgments.

2.11 SIZE AND CONTINUITY OF THE VISUAL FIELD

CIG displays vary as to their available peripheral coverage. The extent of peripheral coverage may be a major factor in determining whether the display creates a realistic impression of self-motion. Recent research (Johansson, 1977; Lee and Lishman, 1975) showed that certain forms of motion in the periphery are sufficient to create an impression of self-motion, even in the presence of conflicting information in the central region of the visual field.

The importance of including peripheral motion in CIG displays in order to create an impression of self-motion depends on the answers to several questions, some of which may be found in existing literature and some of which will require additional research. First, Is peripheral motion necessary as well as sufficient for visually induced perceived self-motion? A sufficiently dense pattern of moving edges or texture elements in the central field may substitute for peripheral coverage to induce a realistic impression of self-motion in CIG displays.

A second question is whether perceived self-motion is important for transfer of training. As there is very little literature on transfer of training using CIG displays, an answer to this question may require new research.

Finally, there is the question of which information must be displayed in the periphery to create an impression of self-motion. The literature suggests (e.g., Koenderink, et al., 1978) that neither realism nor high detail is needed to represent the peripheral scene, a result that is consistent with the low acuity of peripheral vision. A moving random texture is sufficient, and even a simple line pattern may be effective.

Although a display with minimum detail in the periphery may be sufficient to produce an impression of self-motion, such a display could reduce the realism of the simulation if the trainee turns and looks directly at the display. A potential solution to this problem is to adjust detail according to sensed direction of gaze (see Subsection 2.10).

Another peripheral-coverage problem noticeable in present CIG systems is the difficulty of aligning the pictures on adjacent monitors. The extremely high vernier acuity of human observers may make it impossible to adjust adjacent monitors in current systems well enough to prevent noticeable discontinuities in edges that continue from one monitor to the next. Discontinuities are also noticeable in motion paths when an edge moves from one monitor to an adjacent monitor. These discontinuities interfere with the realism of the simulation. There is literature on vernier acuity from which the detectability of discontinuities in CIG displays could be estimated. Several studies (e.g., Grahm, 1965) have found that discontinuities as low as 2 seconds of visual angle are detectable. There is a similar problem in color matching when a uniform surface is displayed on more than one monitor.

2.12 HYBRID DISPLAY AND UPDATE RATE

There are problems specific to hybrid (combined calligraphic and raster) displays, and a closely related problem in raster displays whose update rates are slower than their refresh rates. One problem specific to hybrid displays is a tendency for the calligraphically generated points to appear closer than the raster-generated edges. Runway markings, for example, appear to be below the level of the runway lights. This effect is probably due to the sharper focus of the calligraphic portion of the display. The relevant perceptual literature is that dealing with the effects of image resolution on apparent distance.

In a hybrid system, adjacent features generated by the two methods are not displayed at the same time. For example, there may be a delay between the plotting of the runway edge lights and the plotting of the surface markings. Although the lights and surface markings may be correctly positioned on the display screen, the time delay may result in a perception that the lights and markings are misaligned. This misperception probably occurs when eye movements take place between the times of the calligraphic and raster plots, but the role of eye movements has not been confirmed.

Misperceptions resulting from the plotting of adjacent portions of a display at different times can also occur in pure raster displays if the update rate is slower than the refresh rate. In some CIG displays, the information displayed is updated 30 times per second, while either an odd or even field is refreshed every 1/60 of a second. A dot moving across a display should appear in a new position at every refresh, whether of the odd or even field. If the display is not updated at every refresh, however, the dot will be frozen in position for each frame, appearing once in that position in the odd field and again in the same position in the even field. This representation is not consistent with the smooth motion of a single dot in direct vision. It results in the perception of two dots, separated in space by the amount of motion that should have taken place between the odd and even refresh times, while only one dot is intended in the display. (The same effect occurs in motion pictures: a rapidly moving dot appears to double or triple, depending on whether a projector displays each frame two or three times before moving to a new frame.)

The perceived doubling of points and edges in raster displays that update at the frame rate rather than at the field rate has at least two potential consequences. The less serious consequence is that the doubling may be distracting and reduce the display's realism. The more serious consequence is that the perceived separation of the doubled points or edges is a potential cue to velocity that does not exist in direct vision. If a trainee learns to judge velocity on the basis of these double images rather than on the basis of cues that exist in direct vision, these judgment skills will not transfer to actual flight conditions.

The occurrence of multiple images under conditions similar to those described above has been documented in the perception literature (e.g., Braunstein and Coleman, 1966). The seriousness of this problem for transfer of training needs to be examined in order to determine the importance of updating at the field rate.

3. ADVANCED ALGORITHMS RELATING TO LIMITATIONS

By investigating existing CIG simulators and the current data on human perception, we have been able to identify twelve limitation areas and their psychological bases, and to suggest methods or requirements for reducing or eliminating their effects. In this section, we use our knowledge of the techniques used in existing advanced CIG simulators and the technical and mathematical foundations of CIG simulation to derive sets of algorithms, optimal conditions, and recommendations for reducing or eliminating the limitations of some current CIG techniques.

These algorithms, conditions, and recommendations can be grouped into four distinct areas. The first area concerns aliasing controls. Certain operations and conditions are necessary for optimal perception because of the display's sampled data format. The second area concerns various scene and environment models. Existing systems lack important models (i.e., atmospheric attenuation and scattering) or use methods (e.g., level-of-detail controls) that produce inaccurate models. The third area concerns display properties. The display hardware is limited in several ways (e.g., resolution), and there are proper and improper (e.g., visible shadow mask) ways to set up a display. Filters can enhance contrast perception and thus permit increased apparent contrast without increasing the CRT's output. The fourth area concerns future algorithms. New approaches can eliminate the inherent limitations in the planar polygon approach of existing simulators. With the new approaches, the density of displayed information will increase, and the temporal dynamics of changing reflection geometry will result in tonal variations according to more accurate reflection models, including shadows.

3.1 ALIASING CONTROLS

The basic underlying display model is continuous across the screen in space (i.e., an image is a continuous scalar intensity function) and time (i.e., continuously varying perspective changes in time). The basic hardware display model is sampled, with a two-dimensional sample array for each frame and a sequence of fields displayed sequentially at regular intervals. The difference between the underlying continuous function of space and time and the hardware display of discrete samples produces aliasing. That is, aliasing is the error or misrepresentation that results when a continuous image is represented by an array of discrete samples. A classical example of aliasing is the "staircasing" effect that results from a discrete sampling of a slanted line.

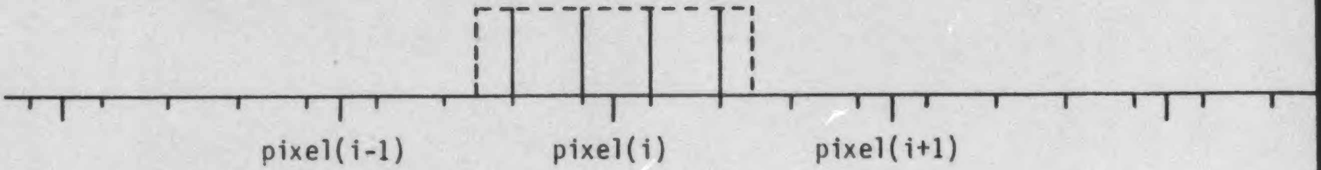
Sampled data representations of any continuous function suffer some artifacts because changes in the function's surface that occur rapidly with respect to the sampling interval are improperly represented. The mathematical theory underlying this effect precisely states what happens in terms of the Fourier spectrum. However, the theory requires sophistication for a full appreciation and proper application.

The human visual system operates in an illusively simple way. While a complete model of the process of human visual perception has not been developed, there is extensive knowledge on how the eye works. This knowledge dictates how to optimally drive the vision system, especially in regard to aliasing controls.

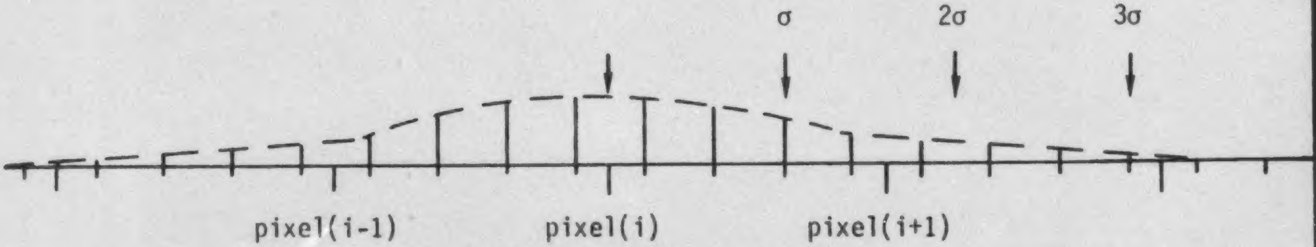
3.1.1 Gaussian Impulse Response

The eye can be heuristically modeled as having a Gaussian response. An improved algorithm to reduce aliasing should include this Gaussian model. The basic algorithm suggested by TSC involves a Gaussian weighted average of the scene samples around each pixel with the standard deviation equal to $2/\pi$ multiplied by the sample spacing. Figure 2 illustrates this situation. The two screen dimensions can be handled independently because they are orthogonal.

The algorithm's classical explanation relies on Fourier analysis. What happens is as follows: 1) convolve the underlying continuous scalar function with a Gaussian impulse response of standard deviation $2/\pi$ of the pixel interval, 2) sample the pixels, and 3) reconstruct the underlying continuous function by a lattice of Sinc functions with scalar magnitudes, each equal to the corresponding sample value. The result of these steps is that a minor amount of energy is aliased. The worst case of aliasing


pixel(i-1)
pixel(i)
pixel(i+1)

Constant Weight, 4 by 4 Samples per Pixel


σ
2σ
3σ
pixel(i-1)
pixel(i)
pixel(i+1)

Gaussian Weight, 4 by 4 Samples per Pixel

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Figure 2. Examples of Constant and Gaussian Weights

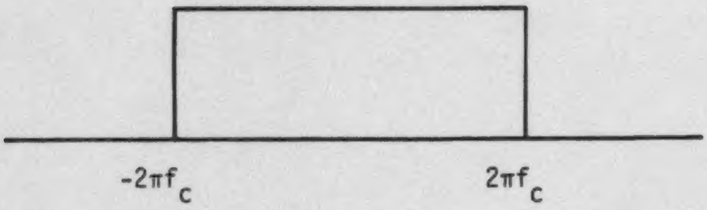
is for a delta function such as a true point light--there will be a maximum of about 5 percent aliased energy (i.e., spectral energy above critical frequency). Since each polygon can be treated separately as a pulse, much less than 5 percent of a surface's energy is aliased in constant or smooth shading of planar, polygonal surfaces.

Because the real process is subtly different from that just delineated, the classical aliasing value represents a theoretical upper bound to performance. The underlying function is sampled at a rate higher than the pixel sampling rate and then averaged. The result is that a Gaussian weighted average of samples is taken about each pixel (as opposed to the true convolution in the classical version). Another difference is that the CRT has a Gaussian impulse response rather than a Sinc function impulse response. These differences compound the analysis and cause results that deviate from the classical results. These results represent an upper bound to aliasing control because, through Parseval's Theorem in analysis, no other sampling method can better approximate the function in a truncated representation based on the sampling rate.

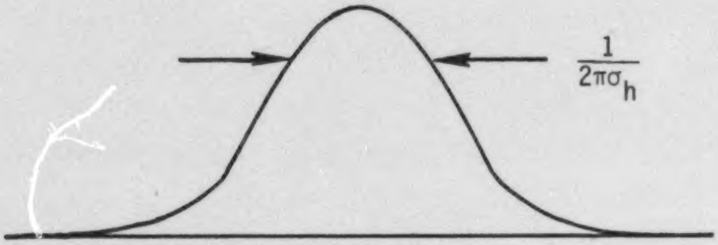
Because of the viewing situation involved, the sampled image is actually not seriously degraded. A human observer is viewing the display screen in a non-diffraction-limited (i.e., light-adapted) condition with a Gaussian impulse response.

When the Gaussian impulse response image is viewed, the hardware's image convolves with the human impulse response. This convolution yields a Gaussian impulse response that has a larger spread than does 20/20 vision. Thus, there is an out-of-focus condition, but there are no aberrations (i.e., the observer is effectively made nearsighted but there are no other consequences).

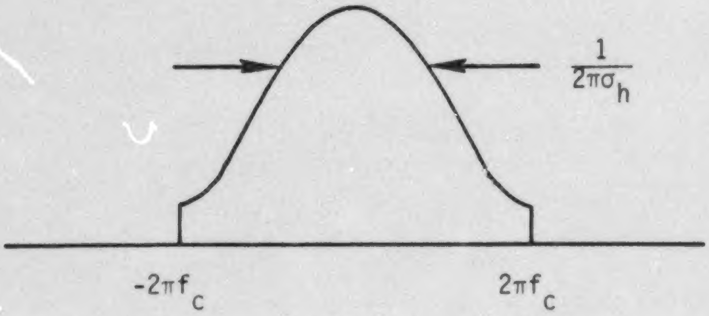
When viewing the lattice of Sinc functions, each Sinc function individually convolves with a Gaussian response corresponding to human visual optics and receptors. This convolution modifies the individual Sinc functions towards Gaussian functions. In the Fourier frequency domain, the Sinc is a pulse from $-2\pi f_c$ to $+2\pi f_c$, where f_c is the critical sampling frequency, as shown in Figure 3. Thus, convolution truncates the Gaussian at the critical frequency. If the critical frequency, f_c, is two


$-2\pi f_c$
$2\pi f_c$

Sinc Function Response


$\frac{1}{2\pi\sigma_h}$

Gaussian Response


$\frac{1}{2\pi\sigma_h}$
$-2\pi f_c$
$2\pi f_c$

Perceived Response

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Figure 3. Convolution of Human Response and Display

or more times $1/2\pi\sigma_h$, where σ_h is the standard deviation of the human visual impulse, then the result closely approximates a generating lattice of Gaussians that each have a standard deviation of σ_h. Substituting a Gaussian for a Sinc function on the CRT face thus does not significantly change the perceived impulse response as long as the critical frequency is at least two or three times the Fourier spectral frequency $1/2\pi\sigma_h$.

The above discussion is based on standard signal analysis. As such it is important but unduly pessimistic. The reliance on global operators limits the results to global information. However, the CRT is composed of a two-dimensional array of local pixel areas. For the sampling approach just described, the aliased energy is within a pixel of its correct position and the variance of the amount of aliased energy decreases with the number of samples if there are no aliasing controls. Figure 4 shows the case of a point light displayed using uniform sampling. The point is near the common corner of all four pixels so that all four should have about equal illumination, but only pixel (2,2) is bright. Effectively, 75 percent of the point's energy is aliased. The observed impact is minor if the apparent resolution of the pixels is small with respect to human resolution. There are two points here: 1) classical Fourier analysis is useful but unduly pessimistic and not directly applicable to CIG, and 2) uniform weighting produces a large amount of aliasing.

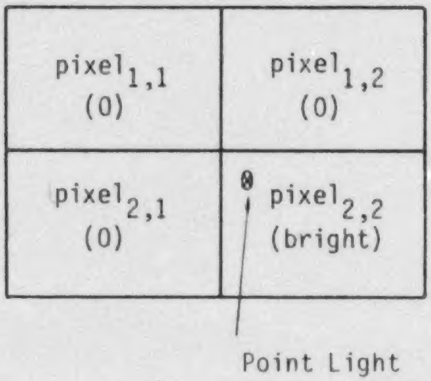

Figure 4. Point Light Using Uniform Weighting

The Gaussian impulse response involves oversampling just as is done in existing systems. The samples are summed with the proper Gaussian weights (Note: binomial in good approximation to Gaussian), and the value is displayed at a point in the frame. The added cost of the Gaussian weights is hard to estimate, but they will not require a hardware approach that differs much from existing oversampling approaches. Actually, it may be significantly cheaper to use the Gaussian weights since oversampling can be reduced with a potential reduction of the number of samples by 75 percent (e.g., from 8 x 8 to 4 x 4 oversamples for each pixel) and a significant improvement in image appearance. The same level of improvement cannot be accomplished by defocusing the CRT because the underlying aliasing effects occur prior to the CRT display. Based on the experience of several researchers who found that edge detection is basically unaffected by the Gaussian impulse response (see Subsection 2.2 and Liebowitz in Appendix B), the practical resolution will remain the same. This algorithm will become more important as displays grow denser with features. Constant or other weighting can never achieve the accuracy of Gaussian weighting because the latter 1) provides aliasing control, 2) matches the human impulse response, and 3) does not degrade edge detection ability beyond signal-to-noise effects.

3.1.2 Frame/Field Conditions

The underlying hardware display model involves a sequence of frames that each have the Gaussian impulse response described above. The sequenced frames are displayed one at a time, in order, and at a fixed rate. Typically, 30 to 60 frames/sec are displayed.

The frames are usually divided into two fields (one of even lines and one of odd lines) that are displayed sequentially in order to double the effective refresh rate. The intent of this procedure is to avoid flicker perception and concomitant eye strain. At 30 frames/sec, prolonged viewing causes eye strain with accompanying symptoms such as fatigue and headaches. At 60 frames/sec, unlimited viewing at typical illumination levels for the screen and background causes no significant fatigue. A frame divided into a sequence of two fields may be acceptable for most applications, but the use of one eye position for both fields of a frame causes serious perceptual difficulties under dynamic motion conditions.

Figure 5 presents the problem of dual competing images, which is an aliasing problem and a mismatch at the man/machine interface in the area of multiple displays of each frame. Several experiments have shown that test features such as points break up into separate features when moved more than a certain distance between frames. The human is able to track one separate, smoothly moving feature for each showing of the same frame. The only appropriate solution is to show each frame once.

The best approach for high visual fidelity is to display a frame as a single field. The display is a sequence of frames shown at a rate of 60 frames/sec or faster. The full frame display drives the visual system properly with no noticeable temporal delays in any local area of a few degrees, which is what happens in an actual scene. The rate of 60 or more frames/sec is fast enough to avoid flicker. This frame rate also reduces the incidence of temporal aliasing such as strobing and motion reversal.

An obvious (and poor) approach is to display a frame as two fields with separately computed perspective geometries. The display is a sequence of frames shown at a rate of 30 frames/sec or more, with a field rate of twice the frame rate. The display of alternate rasters causes problems with visual perception because of the changes occurring on the frame in a local area of alternating rasters about the receptive field of each receptor cell. The effect is not as simple as multiple competing images because there will be aliasing effects due to temporal changes in the image. Features will change shape or even disappear under some motion conditions. Thus, the use of two or more fields per frame is not perceptually acceptable for high dynamic motion applications if the refresh rate per field is 30 frames/sec. There is no evidence of deleterious effects, however, when the refresh rate is 60 frames/sec even with split fields.

Implementing a single field per frame at 60 or more frames/sec is more expensive than the standard video format. The bandwidth is basically doubled for this high bandwidth channel. While the cost can be

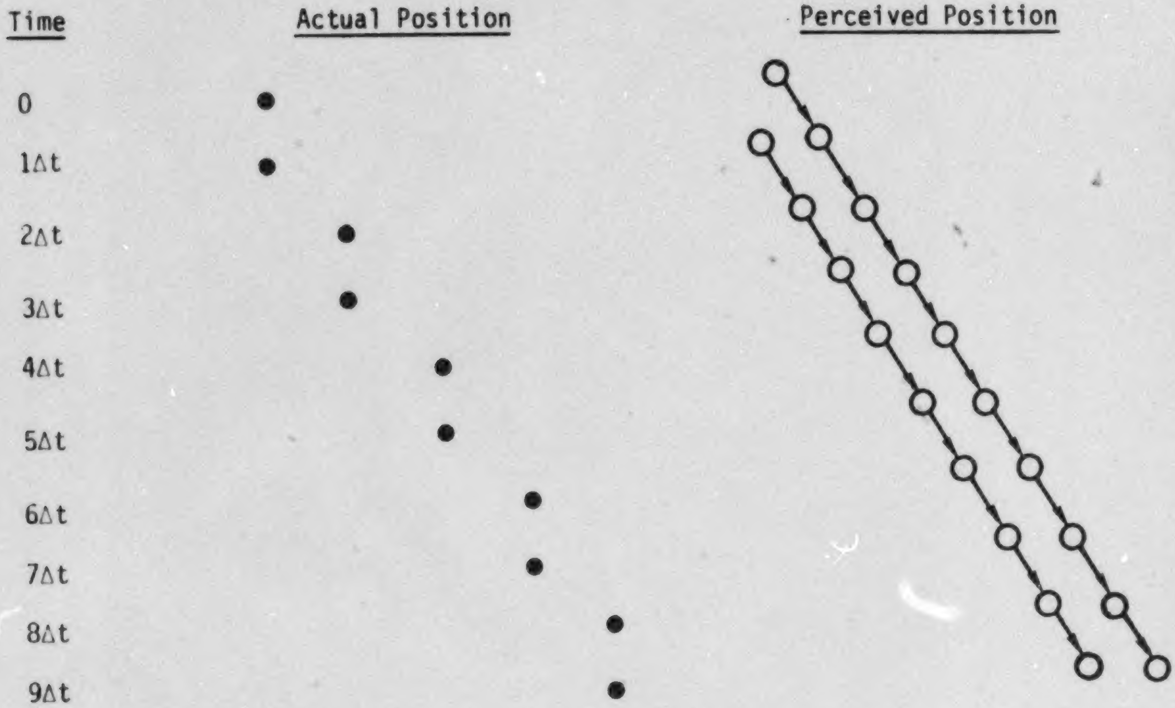
Time
Actual Position
Perceived Position
0
1Δt
2Δt
3Δt
4Δt
5Δt
6Δt
7Δt
8Δt
9Δt

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Figure 5. Perceived Effect of Displaying Each Frame Twice

reduced by lowering the frame resolution for some applications, it must be borne for high performance simulations so that aliasing effects on images will not occur.

3.1.3 Hybrid Picture Effects

The basic underlying hardware display model is a sequence of 60 or more frames/sec in which each frame has a single field and a Gaussian impulse response as discussed above. With hybrid picture displays, several special effects are used in addition to the display model. These involve using combined raster and calligraphic writing (e.g., minirasters) for selective high resolution. However, as explained next, serious difficulties result from using both general calligraphic and miniraster hybrid displays.

The use of combined raster and calligraphic displays produces improper perceptions which are very noticeable under dynamic motion conditions (see Subsection 2.12). For example, point lights simulated by calligraphic elements seem to float in space and shift around, leading or trailing the rest of the scene. This problem is caused by the timing and resolution variations between the raster output and the calligraphic output.

The timing delay between the raster features and the calligraphic features can be up to 33 msec in any local screen area. This delay results in a net motion due to aliasing of calligraphic and raster picture elements under motion conditions.

Because the calligraphic features are overwritten on the raster display so that they are not subject to the aliasing affects of the rasters, they appear in front of the raster pattern with its imagery. The lack of raster effects for calligraphic features actually works against a valid integrated perception. Using a higher resolution calligraphic beam further separates the raster and calligraphic features perceptually.

The use of hybrid raster/calligraphic displays is inherently limited to low dynamic motion simulations. The timing and resolution mismatches cause significant errors in perceiving motion and distance. The lack of a raster aliasing mask for calligraphic features also separates the two formats perceptually.

The basic ground rules are to 1) set the timing of all features exactly the same in any local areas of several degrees of apparent resolution, and 2) keep a constant resolution for targets and their immediate backgrounds. These rules restrict the use of hybrid raster and calligraphic displays to simulations in which the detrimental effects are acceptable.

3.2 SCENE, ENVIRONMENT, AND SENSOR MODELS

The simulation model involves a scene, an environment, and a sensor. The scene model includes surface geometry and materials together with special pointers and parameters applicable to the environment and sensor models. The environment model includes point and extended sources of electromagnetic energy in a spectral band(s), atmospheric conditions (e.g., attenuation, temperature, rainfall rate), and albedo conditions. The sensor model includes reflective (or emissive) material properties, scanning format, impulse response, spectral band(s), and field of view.

Existing real-time CIG simulators necessarily implement only the crudest models in order to reduce cost and maintain real-time throughputs. The present study identified areas of these models that can significantly improve human perceptual accuracy if properly upgraded. In the scene model, the use of artists to build data bases can improve the realism of the scene, and some improved level-of-detail algorithms can eliminate the frequency jumping of objects into and out of the display image. In the environment model, the use of an atmospheric attenuation and defocusing model should considerably improve perceptual accuracy. The sensor model comprises the reflection (or emission) models for scene materials and tone application models. These models involve the sensor measurement and display of received energy (e.g., mono- or multispectral, polarized, intensity, range). Diffuse reflection and emission models and Gouraud shading are now used, but there are serious limitations with these models.

3.2.1 Atmospheric Attenuation and Scattering

Electromagnetic energy transmitted through the atmosphere interacts with the homogeneous gases and locally variable gases and aerosols. Molecular absorption attenuates energy at a negative exponential rate. Aerosol and particulate scattering attenuates energy at a negative exponential rate along the line of sight and also defocuses the energy via multiple scattering. These effects are due to inhomogeneities, but they are only significant at vary long ranges or low grazing angles near surfaces where convective heat transfer causes atmospheric "boiling."

This subsection discusses three atmospheric models: an attenuation model, a defocusing model, and a color model. These models are more complex than those in current CIG simulators. The perceptual benefit added by these models should be evaluated (see Section 4) before they are included in future CIG simulators.

An attenuation model determines what fraction of the energy traveling along a ray from a transmitting point (on a surface or in a volume) continues on the ray to a second reception point. Molecular absorption and first-order scattering along the ray are modeled by a scalar attenuation coefficient, $\alpha(r)$. This model is a first-order linear differential process:

$$\overline{I}_R = I_0 \cdot \exp\left[-\int_0^R \alpha(r)\, dr\right] \quad ,$$

where I_0 is the intensity (i.e., radiance or Power/Projected Area-Steradian) at the original point; $\overline{I}_R$ is the intensity at range R; $\alpha(r)$ is the attenuation rate (1/dr) due to absorption and scattering (i.e., $\alpha(r) = \alpha_a(r) + \alpha_s(r)$) at range r; and r is the range variable.

The atmosphere is adding energy in its own characteristic spectrum along this ray due to molecular emission by atmospheric gases and to aerosol scattering of other energy from various sources in the scene. This addition of energy is a first-order linear differential process:

$$\hat{I}_R = \int_0^R \beta(r) \cdot \exp\left[-\int_0^r \alpha(u)\,du\right] dr \quad ,$$

where $\hat{I}_R$ is the intensity at the receiver point (R units from the transmitting point), $\beta(r)$ is background intensity rate dI/dr, and the background attenuated energy is summed from ranges 0 to R. For practical purposes, α and β can be set constant so that

$$\bar{I}_R = I_0 \cdot \exp(-\alpha R)$$

and

$$\hat{I}_R = \beta \cdot \int_0^R \exp(-\alpha r)\,dr$$

$$= \frac{\beta}{\alpha}\,[1 - \exp(-\alpha R)] \quad .$$

Setting I_a equal to β/α, the received energy along the ray from a transmitting point to a receiving point is

$$I_R = I_0 \cdot \exp(-\alpha R) + I_a \cdot [1 - \exp(-\alpha R)] \quad .$$

This attenuation model is useful for determining the attenuated line-of-sight intensity of point samples in the scene. It is inaccurate in how it models aerosol scattering, but it produces an accurate perception of aerial perspective. This attenuation model appears to be the most acceptable in terms of computational simplicity.

The real situation is more complicated. For example, some nights the moon has a halo and street lights blur into the distance--a case of higher-order scattering effects that are not handled by the above attenuation model because it only deals with first-order scattering along the line of sight. If no other scattering occurred, the scattering photons would never be received, and the attenuation model would be accurate.

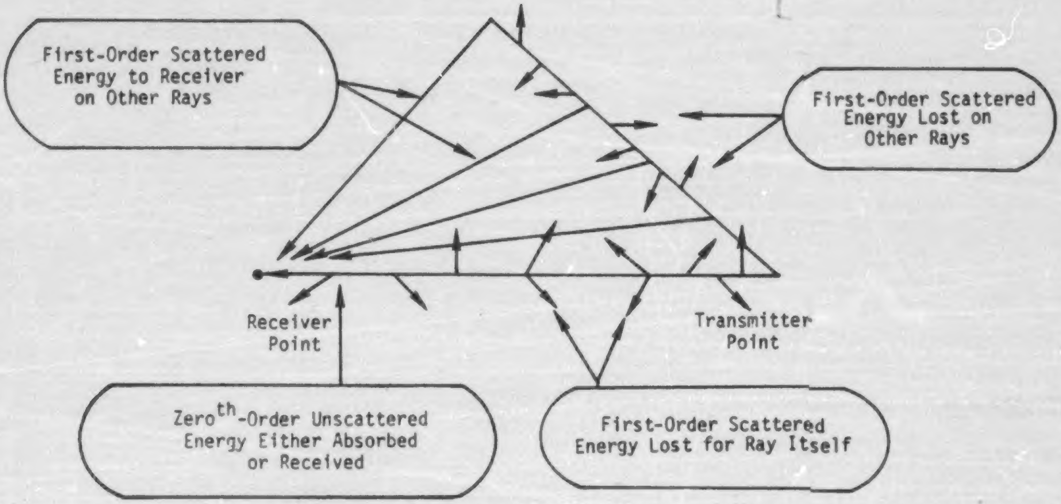
First-, second-, and higher-order scattering of a point's radiation can occur in amounts large enough to produce halos and defocusing (different effects due to scattering phenomena) when atmospheric conditions produce significant scattering rates.

A defocusing model determines the effect of scattered photons in terms of their angular distribution about a point source. This situation is simple: very few of the photons make the journey to the receiver point without incident, and the remaining photons are either 1) scattered away or absorbed or 2) scattered but able to subsequently travel to the receiver point (i.e., general first- and higher-order scattering). Figure 6 illustrates the situation. The attenuation model presented above is used to determine the unaffected fraction of photons. These photons can be focused into a valid perspective image that is only limited by the receiver's aperture. The remaining photons are those that either disappear or are scattered to the receiver. These photons can never form a focused perspective image.

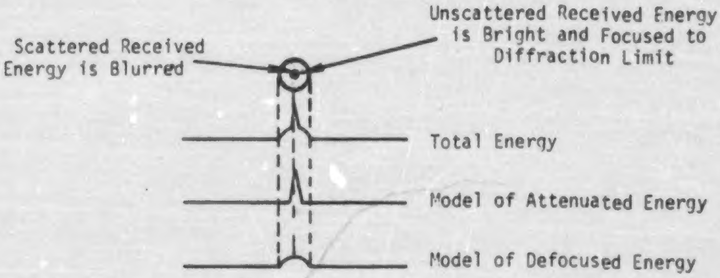
The defocused energy can image into a variety of point spread functions depending on energy spectrum, distribution of particle sizes, and geometry. The common point spread result is close to Gaussian. There are specular scattering effects such as rainbows and halos, but these seem unnecessarily difficult to model. The Gaussian point spread function for the defocusing model seems physically accurate based on models of higher-order scattering that assume diffuse scattering of photons off particles.

The best defocusing model is a Gaussian point spread function:

$$\tilde{I}_R(\Delta x, \Delta y) = \delta \cdot I_0 \cdot \frac{\exp(-\alpha_a \cdot R)}{2\pi\sigma^2} \exp\left[\frac{(\Delta x^2 + \ y^2)R^2}{-2\sigma^2}\right]$$


First-Order Scattered Energy to Receiver on Other Rays
First-Order Scattered Energy Lost on Other Rays
Receiver Point
Transmitter Point
Zeroth-Order Unscattered Energy Either Absorbed or Received
First-Order Scattered Energy Lost for Ray Itself

Side View with Selected Rays


Scattered Received Energy is Blurred
Unscattered Received Energy is Bright and Focused to Diffraction Limit
Total Energy
Model of Attenuated Energy
Model of Defocused Energy

Front View and Profile at Receiver

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Figure 6. Effect of Scattering and Need for a Defocusing Model

where $I_R(\Delta x,\Delta y)$ is the intensity at a $(\Delta x,\Delta y)$ screen displacement from the imaged point; δ is the fraction of the transmitted radiance (I_0) that is scattered toward the receiver point; $\exp(-\alpha_a \cdot R)$ is the attenuation fraction for the absorbed energy (i.e., $\alpha = \alpha_a + \alpha_s$, where α_s = scattering rate and α_a = absorption rate); $(1/2\pi\sigma^2)\cdot\exp(u/2\sigma^2)$ is the spatial distribution of received scattered energy with standard deviation σ; and u is the projected displacement in the scene at range R to the transmitter point. The free parameters δ and σ are determined in the following ways.

"δ" is greater than zero; it is 1/2 for diffuse surfaces and 1 for omnidirectional point lights. It is the ratio of the total transmitted energy integrated over the sphere (i.e., $\int_0^{2\pi}\int_0^{2\pi} I_0(\phi,\theta)\sin(\theta)\,d\theta\,d\phi$) to $4\pi\, I_0$. Hence, for a diffuse surface,

$$\delta = \frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} I_0 \sin(\theta)\, d\theta\, d\phi}{I_0\, 4\pi} ,$$

and for an omnidirectional light,

$$\delta = \frac{\int_0^{2\pi}\int_0^{\pi} I_0 \sin(\theta)\, d\theta\, d\phi}{I_0\, 4\pi} .$$

This defocusing model is physically accurate for diffuse surfaces and omnidirectional lights up to diffuse scattering. The underlying random walk of scattering and the associated Central Limit Theorem in Probability Theory produce a Gaussian distribution in the limit of a distant point source. This distribution is closely approximated whenever defocusing is perceived. The σ is associated with α_s (i.e., $\alpha = \alpha_s + \alpha_a$) via the Central Limit Theorem in that the intensity of the first scattering is a radially varying function of range r, and is a negative exponential distribution with mean zero and variance $\sigma_{\alpha_s}^2 = 2/\alpha_s^2$. Each point in space of first scattering becomes a new energy transmitter with the same statistics (as long as the receiver range is two or more times the distance $\sigma = \sqrt{2}/\alpha_s$, so that a spherical geometry can be used). The Central Limit Theorem states that the effective defocused energy distribution is Gaussian with $\sigma = \sqrt{2}/\alpha_s$.

The defocusing model is difficult to compute using existing polygon shading techniques because range to each sample point is required. (See Subsection 3.2.2 for further discussion.)

A color model treats spectrally varying effects of attenuation and defocusing. The absorption and scattering rates vary spectrally over the visible band, a fact that is apparent in the red sunsets and sunrises and the blue sky albedo. Mie and Rayleigh scattering models represent low scattering changes as a function of aerosol particle sizes and wavelength. The average attenuation rate, α_i, the average scattering rate, α_{si}, and derived parameters such as I_{ai} and σ_i can be computed for each spectral band, i. These bands are red, green, and blue for color displays.

The implementation of a color model involves independent attenuation and scattering computations for each spectral band. The effects include hue gradients due to aerial perspective and changes in source illumination hue due to transmission through the atmosphere to the scene.

There are three interrelated atmospheric models: attenuation, defocusing, and color models. They require the range to each sample in addition to the atmospheric parameters α, α_s, and I_a. The tone application methods presented next discuss how to apply these models to points, lines, and surfaces in the scene.

3.2.2 Tone Application Methods

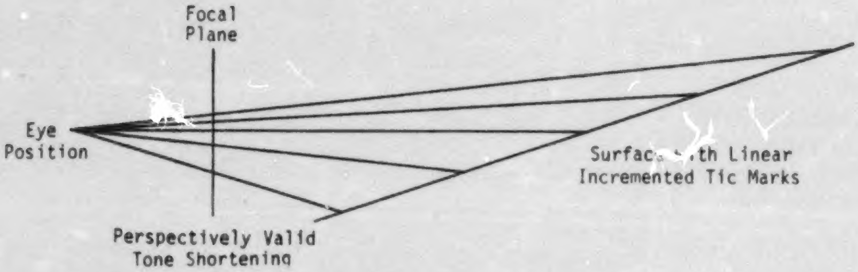
The scene consists of a set of primitive surfaces. The commonly used surface primitives are planar, polygonal bounded surfaces and point lights. A tone application method is an algorithm for applying the sensor tonal measurements of a primitive surface to that surface's projection on the image plane.

A tone application method involves computing a primitive surface's display value at a set of its points and interpolating between these sample points. There are a number of tone application methods used for primitives that are points, line segments, and planar polygons.

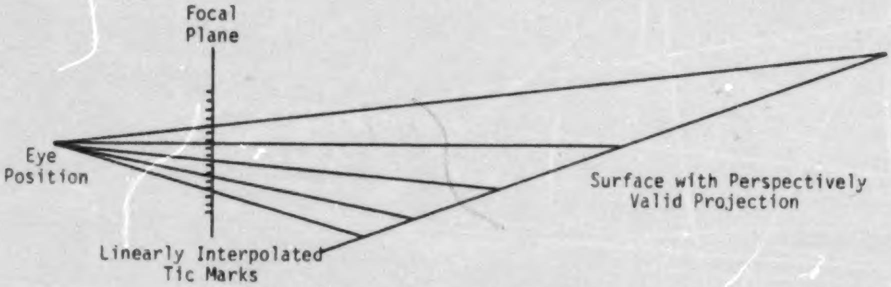
The simplest tone application method is constant shading. One surface point (e.g., the centroid or the first vertex) is modeled and the computed tone is applied across the surface. The tone application proceeds raster by raster, placing the surface's tone in pixels where the projected surface lies.

A common tone application method for line segments and planar polygons is Gouraud (or smooth) shading. This method relies on the sensor measurement being computed at each vertex. The method first linearly interpolates tones along edges between the vertex endpoints and then linearly interpolates between edge tones for individual pixel tones. The difficulty is that the interpolations are computed for the projected surface vertices, edges, and interior points (i.e., the tonal interpolation is linear when viewed in the image plane). The linear appearance is perspectively invalid. There is no perspectively proper tonal gradient compression, and improper foreshortening results, as shown in Figure 7. (See Appendix for perspective literature.)

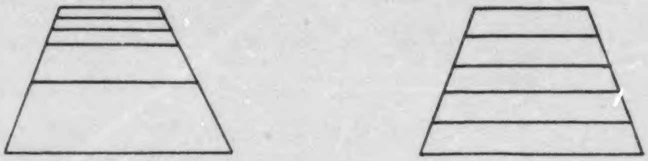
The case of even incremental sampling in the scene space is shown in Figure 7a. This type of sampling results in uneven increments in the image plane (i.e., the display). Thus, if the scene has a linearly varying tonal gradient, a linearly varying tonal gradient in the image plane (as with Gouraud shading) can result only with unequal sampling in the image plane. The companion case is shown in Figure 7b in which even pixel sampling in the image space results in uneven sample increments in the scene space. With the example of a linear tonal gradient in the scene, a nonlinear tonal gradient exists in the image plane. Figure 7c shows a perspective view in the image plane of a rectangle in the scene space (e.g., a runway). As discussed for Figures 7a and b, there is a tonal gradient across the surface in the image plane, as sketched in Figure 7c,


Focal
Plane
Eye
Position
Surface with Linear
Incremented Tic Marks
Perspectively Valid
Tone Shortening

a. Side View of Linear Surfaces Interpolation


Focal
Plane
Eye
Position
Surface with Perspectively
Valid Projection
Linearly Interpolated
Tic Marks

b. Side View of Linear Image Plane Interpolation



c. Perspectively Valid Tonal Interpolation

d. Gouraud Interpolation

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Figure 7. Perspective Effects on Linear Interpolation of Surface Tones

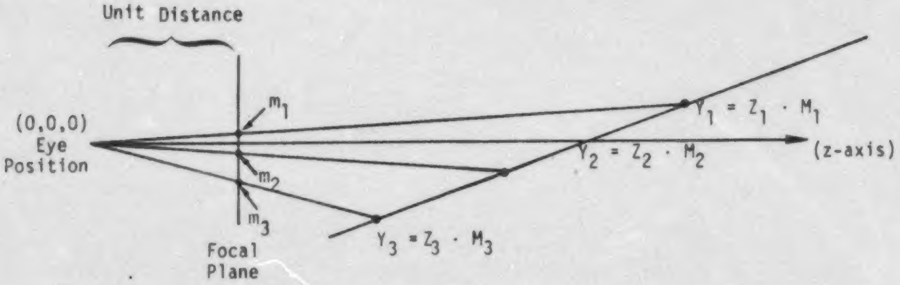
which results in a perspectively proper tonal gradient compression. Gouraud shading, however, samples the projected surface and thus results in the linear tonal interpolation of Figure 7d.

Although Gouraud shading is used on advanced CIG simulators, it produces a significantly erroneous tonal gradient that contributes to aperture mode perception such as surfaces "standing up" orthogonal to the line of sight.

Another tone application method (not used on real-time CIG simulators) is Phong shading. This method is similar to Gouraud shading in that, on the image plane, the surface normal is linearly interpolated among vertices (instead of among computed tones). The surface normal at each pixel is used to compute the tone there. This method suffers from the same perspective inaccuracy as Gouraud shading.

TSC developed a new shading method during the current program. This method, which belongs to the family of smooth or untextured tone application methods, is perspectively accurate (thus producing foreshortening) and provides a range to each pixel sample. It is discussed next, and then textured tone application methods are discussed.

The shading method denoted by TSC as the inverse range shading method applies to line segments and planar polygons and requires that the sensor tonal measurement and the boresight (i.e., z-axis value) range be computed for each vertex. The method linearly interpolates 1/range on the screen along projected edges and uses the actual surface position to linearly interpolate tone back on the surface in the environment three-dimensional space. The method linearly interpolates the 1/range values along the raster, at each pixel sample, and linearly interpolates tone in the surface in three-dimensional space. In this way, the surface tones are interpolated across the planar extent at pixel samples but are interpolated on the surface in the unprojected three-dimensional space. This technique can be used to interpolate surface normals, apply texture, etc. Figure 8 presents the underlying perspective geometry. The computational complexity for each sample can be reduced to an addition and inversion for the z value and two additions and a multiplication for


Unit Distance
(0,0,0)
Eye
Position
m_1
m_2
m_3
Focal
Plane
$Y_1 = Z_1 \cdot M_1$
$Y_2 = Z_2 \cdot M_2$
(z-axis)
$Y_3 = Z_3 \cdot M_3$

Side View of Perspective Geometry

$$\frac{1}{z_2} = \frac{1}{z_1} + \left(\frac{m_2-m_1}{m_3-m_1}\right) \cdot \left(\frac{1}{z_3} - \frac{1}{z_1}\right)$$

$$t_2 = t_1 + \left(\frac{y_2-y_1}{y_3-y_1}\right) \cdot (t_3-t_1)$$

Note: The X and Y surface coordinates each have a constant tone gradient Δt_x, Δt_y and a constant 1/range gradient Δz_x, Δz_y.

$$\frac{1}{z_2} = \frac{1}{z_1} + (m_2-m_1) \cdot \Delta z_y$$

$$t_2 = t_1 + (y_2-y_1) \cdot \Delta t_y$$

$$= t_1 + m_2 \cdot z_2 \cdot \Delta t_y + y_1 \cdot \Delta t_y$$

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Figure 8. Geometry of Inverse Range Shading

the tone. The z value can be used for range in atmospheric models if the field of view is narrow; otherwise, slant range can be calculated by SQRT $[(N\cdot Z)^2 + (M\cdot Z)^2 + Z^2]$.

The use of textured tone application methods goes beyond linear interpolative methods to precomputed and stored tonal maps. A tonal map can be represented as a sample array, a function, or a set of locations and texture primitives. It consists of locally varying tonal modulations around the mean.

Developmental studies were performed on two-dimensional tonal texture (Stenger, Dungan and Reynolds, 1979) and three-dimensional elevation texture (Dungan, 1979) using the texture tile approach. Various CIG manufacturers have developed periodic modulations, bombing patterns, and model features such as trees.

All these methods share one perceptual effect. They produce a statistical (or deterministic in some methods) distribution of detectable features or areas in contrast with their surroundings. This aspect of textured tone application methods is a distinct perceptual advantage over smooth shading methods because the textures, under dynamic motion, drive the human motion-field visual system with a high density of small moving targets.

Although there is a significant amount of research on textured shading, much of it is not available in the literature. This research area is important. The issues revolve around 1) the need for texture if tonal gradients and hue gradients via inverse range shading are not sufficient, and 2) the effects of candidate textured shading methods in human perception (see Appendix B).

3.2.3 Reflection Models

Existing CIG simulators use the simplest reflection (and emission) model: Lambertian or Cosine Law reflection. The surface radiance is constant over the hemisphere above the surface.

There are more accurate reflection models. Some are diffuse plus specular in that the Lambertian diffuse component is used as before, but a specular component reflecting the spectrum of the source is added to the diffuse. Others are general bidirectional in that the angular locations of the energy sources and the receiver are modeled in a somewhat unconstrained model. There is some literature on these models (e.g., Torrance and Sparrow, 1967).

The reflection and emission models that are not simple Lambertian constant radiance models provide perceptual information at a subresolution level. Under dynamic motion conditions, specular reflection provides motion perception information of high precision at an effective resolution finer than the pixel extent. The perception occurs as surfaces translate and rotate in a continuous manner. The specular peaks and angular tonal gradients provide rate of motion and surface orientation information.

There is no one best reflection model for CIG simulators. Since more advanced tone application methods may be used, it is important to consider nondiffuse reflection computed at pixel sample points. This combined reflection and tone sampling approach permits nondiffuse modeling in a real-time simulator with an algorithm that is truly linearly complex and can be pipelined. The resulting simulation would be a significant improvement over the cartoonlike and dull appearance of present imagery.

One other reflection model is shadowing, which can be performed off line for a specified sun position and then left alone or updated periodically. Atherton, Weiler, and Greenberg (1978) produced an algorithm that provides shadow computation by projecting surfaces from a point source of energy onto the scene's surfaces. Shadows can be important at some times of day for some missions, so that the ability to compute shadows and store them as surfaces is necessary for some training simulations.

3.2.4 Level-of-Detail Controls

The level-of-detail controls in existing CIG simulators are used as a data overflow protection. To keep surface and edge density within hardware capability, the range for switching an object's level-of-detail model is adjusted. This adjustment causes objects and their higher resolution detail to visibly jump into and out of the frames.

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There is no cure for improper level-of-detail transitioning. A minimum acceptable transition range for increasing level of detail exists and must be respected regardless of overload conditions. The use of proper aliasing controls and atmospheric models can significantly reduce the minimum level-of-detail transition range by reducing contrast and eliminating aliasing. These two factors (discussed in Subsections 3.1.1 and 3.2.1) should improve the situation.

The extension of the set of primitive surfaces to include points and line segments along with planar polygons reduces edge and surface requirements. The reduction in requirements can be very high because the major portion of the scene in the field of view is at long range where whole objects appear as simple points and line segments. This representation is much easier to compute than are box or other low level-of-detail representations.

If level-of-detail controls do not bring in the object level of detail at the required range, transitions will be observed. Contrast management and more efficient low level-of-detail representations can considerably reduce the display requirements. In this way, level-of-detail transitions can occur at proper ranges without overloading the CIG simulator.

3.3 DISPLAY PROPERTIES

The display hardware has an important role in determining how the human observer perceives the simulated imagery on the display face. One problem is the perceptual impact of the display face itself, disassociated from the imagery. Another problem is contrast management of displayed tonal range.

3.3.1 Display Face

The display face can detract from the perceptual accuracy of the imagery. Section 2 presented this situation in terms of limitation areas: raster effects (Subsection 2.5), perceived flatness of the display (Subsection 2.9), and size and continuity of the visual field (Subsection 2.11).

The ability of the human to see the boundary of the display's face is a significant false cue to distance and motion in the image. Actually, having the display face imaged at infinity compounds the perceptual error. The boundary of the display face should be hidden from the human observer. The boundary of the field of view should be the cockpit window or, if that is not practical, blinds or curtains should be hung to perceptually isolate the displayed imagery for any field-of-view boundary.

The ability of the human to see the raster pattern is a significant false cue. The presence of a raster pattern imaged at infinity sets the human observer's visual accommodation to infinity when normal accommodation in the absence of stimulation is around 1 m. It also masks the underlying image in the sense of a veil through which one sees the image. The presence of the raster pattern perceptually masks low contrast and small features and prevents their detection.

Proper construction of the raster scan pattern or shadow mask can significantly reduce the masking effect. The human visual system is considerably more sensitive to horizontal and vertical lines than to diagonal lines. Thus, the traditional raster display produces perceptual masking that is worse than it need be. A horizontally and vertically offset display would produce a less perceptible raster pattern.

3.3.2 Contrast Management

The tonal range of the display hardware cannot meet the range of real out-of-window scenes. There are ways to improve the situation by carefully matching the display to the human observer.

In many training simulations, a log (energy) output scale can be used. The resulting display has proper relative contrast but is compressed in the high intensities where humans are less sensitive to intensity variations. This approach is acceptable for most applications.

Another approach is to rely on atmospheric defocusing to blur small, high intensity features so that the energy is spread over more screen area. This approach helps in modeling point lights as they closely approach the observer. At present, the light's size is adjusted to be larger or some other trick is employed to produce perceptually valid point lights.

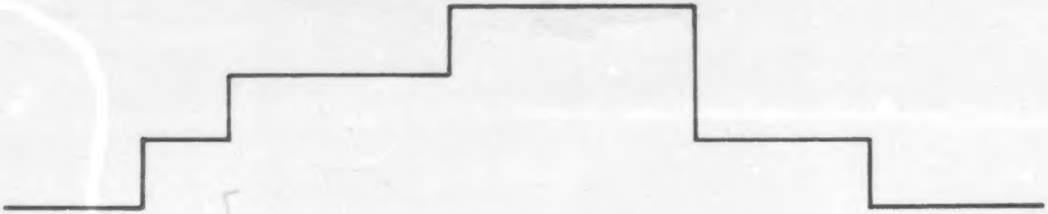
Image filtering is a potential way to manage contrast and obtain a perceived tonal range beyond the capability of the display hardware. Cornsweet's illusion (1970) is a key to the contrast management of the human visual system. A high-pass filter with proper shaping might eliminate the need for much of the display energy while retaining much of the apparent contrast of the imagery. Figure 9 presents the situation along one raster with and without filtering by the Laplacian of the negative exponential distribution. Although the situation shown in this figure is only hypothetical, it indicates the tonal range reduction possible with contrast management via filtering matched to the human visual system. This area needs research and has the potential for large improvement over the limited dynamic tonal range of display devices.

3.4 FUTURE ALGORITHMS

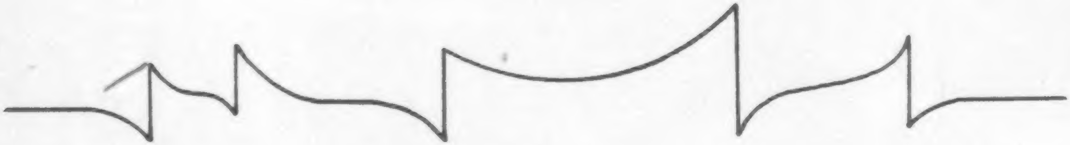
The present state-of-the-art in CIG simulation involves points and planar polygons, diffuse reflection and emission, and only low visibility atmospheric attenuation. There are areas for improvement in the present approach. The set of surface primitives should include points (e.g., spheres, circles, and directional lights), line segments (e.g., cylinders and tapes), and planar polygons. The reflection and emission models might include speculars and shadows. The atmospheric models might include attenuation, defocusing, and color effects. The tone application methods might involve textured shading. Improvements in these areas, which were discussed previously, could benefit CIG simulation based on linear surface primitives.

The intent here is to identify some goals for these new approaches. These methods must be perspectively valid. For example, random noise not fixed to the surface is not a valid simulation approach. There must be aliasing control since as little as 5 percent aliasing noise can mask contrast and thus destroy the appearance of texture.

The central objective of any method is to accurately drive the human observer's perceptual system (see Appendix B, Liebowitz). This concept is difficult to measure and is the central area for future perception research applied to CIG simulation.



Intensity Across Raster of Unfiltered Image



Intensity Across Raster of High-Pass Filtered Image

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Figure 9. Unfiltered and High-Pass Filtered Tonal Ranges

3.4.1 High Density of Features

The full stimulation of the human visual system involves a sufficient density of identifiable features at contrast with their projected surround (i.e., texture). Research indicates that a density of features (e.g., points, blobs, vertices, edges) on the order of 0.5° to 1.5° of apparent resolution is sufficient for accurate motion field perception in the total absence of contrast image information. This work involves human observation of dot fields in motion on a CIG display. Research also indicates that perspectively accurate tonal (and hue) gradients across surfaces can produce accurate depth perception, but the human visual mechanisms need to be further clarified. The dynamic appearance of textures and tonal gradients seems to stimulate visual perception of subjective realism as well as of a feature's motion and distance.

3.4.2 Reflection Models

The use of diffuse reflection and emission results in an information-poor display. Nondiffuse reflection under dynamic motion conditions produces motion and distance information at a resolution higher than that of a diffuse display. This effect stems from the increase in contrast, the temporal variation in tone, and the motion of specular areas and tonal gradients across large projected surfaces as the surfaces move relative to the observer. The total reliance on diffuse reflection is a mistake in that reflectance computations have truly linear complexity that is fixed according to the number of pixel samples taken. The over-reliance on polygons results in a higher density of surface primitives in the scene with associated higher algorithm complexity and statistically variable raster computation.

Reflection using nondiffuse models, texture, and shadows can improve the observer's perception while using considerably fewer surfaces. Historical developments in the CIG community have driven designers to completely rely on diffuse reflection and emission, but it is time to reconsider tradeoffs. Diffuse reflection eliminates a considerable density of motion and distance information in dynamic motion CIG simulations.

4. RECOMMENDED RESEARCH AREAS

Section 3 discussed the CIG algorithm implications for each of the 12 limitation areas that were introduced in Subsection 1.3. This section describes the areas of basic perceptual research that have the most significant impact on the identified limitations.

Subsection 4.1 presents an overview of the research that should be performed, including the basic perceptual questions that the research is to answer. Subsection 4.2 discusses these research areas from an algorithm standpoint.

4.1 AREAS OF PERCEPTUAL RESEARCH

The most pressing need is for research using dynamic scenes. Most of the basic psychophysical research has been conducted with static stimulus displays in which the viewer and the objects viewed do not move. Thus, there are probably severe limitations on applying the conclusions drawn from such research to situations in which the viewer (pilot) is moving rapidly through his environment. For example, although the static psychophysical research indicates that texture contributes little to the accuracy of perception, it may play a far more important role in dynamic scenes. Braunstein's work (1968) would suggest so, but more research is needed.

The proposed research would not require the use of real-time CIG simulator systems. Instead, it could be conducted with laboratory CIG systems or with systems that use motion-picture or video-disc animation, or motion pictures converted to videotape. Psychophysical judgments could be studied using abstractions of the information present in CIG displays. Once sufficient research is conducted using simpler patterns, additional experiments using actual CIG systems might be considered to confirm the conclusions of these proposed experiments prior to making any final design decisions.

Four areas of major importance to perception are recommended for further research: aerial perspective, texture, shadows, and specular reflection. These areas are related and any further research should make use of their interaction.

1. Aerial perspective. Although aerial perspective is widely accepted as a basic cue to relative distance, virtually no research has been performed to assess its actual importance. It is an obvious candidate for inclusion in CIG because it is easy to simulate. Thus, its true effectiveness should be investigated. An important question is whether aerial perspective interacts with and enhances the effect of texture.

2. Texture. There is little research on the effectiveness of texture in dynamic scenes. Also, the effectiveness of three-dimensional texture needs to be examined. Relative motion within the microstructure of the texture might be very important. As mentioned above, the interaction between texture and aerial perspective should also be investigated.

3. Shadows. In theory, the shadows created by directional illumination are a rich source of information to a moving observer. There is relative motion between the object and its shadow, and object and shadow undergo different shape transformations as the viewer moves. Since both of these factors are possible sources of information to the viewer, their actual importance needs to be established by research.

4. Specular reflections. In theory, these can provide information about relative motion, surface definition and orientation, and relative distance. However, research is needed to establish their actual importance.

Two types of dependent measures can also be used. The first type, which assesses the apparent realism of the display, consists of viewer ratings of features such as sense of self-motion, sense of depth in the display, definition of surfaces, and apparent clarity of the orientations and distances of surfaces and objects. The second type assesses the observer's performance on basic perceptual judgment tasks. Such measures would include accuracy of judgment of motion, absolute and relative distances, and orientation of surfaces and objects.

The recommended research for the four major areas is presented next, followed by recommendations for three areas of secondary importance: flatness cues, perceived self-motion, and update rate.

4.1.1 Aerial Perspective

Although aerial perspective is always cited as a cue to distance, there has been virtually no empirical or theoretical analysis of its role in perception. Thus, the research should probably begin with an a priori analysis to define the possible boundaries of the role of aerial perspective. In such an analysis, aerial perspective should be fully defined--for example, it involves a shift in contrast, hue, and saturation as a function of distance and elevation. Although the role of elevation is ignored in most perception texts because they deal with ground-based perception, elevation is an important variable for ~~the~~ flier. Consideration should also be given to the possible roles of aerial perspective in various basic perceptual tasks (not just distance perception) and piloting activities. In addition, the possible interactions of aerial perspective with other types of cues (such as texture) should be considered. Finally, consideration should be given to the ways in which the perceptual importance of aerial perspective might be either increased or decreased by the special properties and constraints of computer-generated imagery (e.g., limited resolution, limited scene complexity). The goal of this phase should be to define the full range of possible roles of aerial perspective and, consequently, the full range of experiments which might profitably be undertaken. It should also be possible to establish priorities for the experiments.

The next part of the research is directed toward establishing the importance of aerial perspective in performing basic perceptual tasks and judgments. The research can be conducted in the laboratory, but would best be done using computer-generated imagery similar to that used in simulators.

The independent variables should include not only the presence of aerial perspective in various degrees, but also the independent manipulation of its contrast and chromatic (shifts in hue and saturation) components. If the chromatic component is found to add little, present weather algorithms can probably be used. Similarly, the dependence of aerial perspective on ground distance and elevation should be independently manipulated. Finally, other cues should be manipulated in order to study their interactions with aerial perspective.

The dependent variables should include measures of accuracy for perception of distance (relative and absolute), size, movement (of observer and other objects), orientation and composition of surfaces, and detection and recognition of objects embedded in the environment.

Another goal of the research is to establish the importance of aerial perspective for a representative set of piloting activities. This part of the research would be best accomplished in a simulator.

Although this research on pilot task performance would probably use the same independent variables that the basic perceptual skills research uses, the dependent variables would be measures of pilot performance in various piloting tasks. Such tasks might include low- and medium-altitude tactical maneuvers (including aerobatics), detection and recognition of ground-based targets, weapons delivery to ground-based targets, detection and recognition of airborne targets, and landing. Another important part of this research would be to measure user-acceptance as a function of the presence of aerial perspective.

4.1.2 Texture

Adding texture to a CIG display may be a useful way to reduce the ambiguity of surface definition, particularly that of surface slant, distance, and relative velocity. This usefulness, however, cannot adequately be determined from the current perception literature because little research has been done on the effectiveness of texture in dynamic (as opposed to static) scenes. Relative motion within the microstructure of the texture might be very important in dynamic scenes. The effectiveness of three-dimensional texture and the interaction between texture and aerial perspective in reducing ambiguities of surface slant or curvature, distance, and relative velocity are important issues that have received virtually no attention in the perception literature.

Research on static textures has generally found that while regular textures are effective in conveying surface slant to observers, irregular textures are definitely less effective and sometimes completely ineffective (Degelman and Rosinski, 1976; J. J. Gibson, 1950; J. J. Gibson and E. J. Gibson, 1957; Levine and Rosinski, 1976; Newman, Whinham, and MacRae, 1973; Rosinski and Levine, 1976). Although research with random textures in dynamic scenes has shown good correspondence (usually with some underestimation) between displayed and judged slants (E. J. Gibson, et al., 1959), this accuracy appears to be based on the velocity gradient information carried by the texture rather than on the texture gradient per se (Braunstein, 1968).

Farber and McConkie (1979) suggest that the velocity gradient may reveal degree of slant while the texture gradient reveals direction, but this hypothesis remains to be tested. This issue is part of an unanswered question that is important to the design of CIG displays: Is texture effective primarily (or exclusively) as a carrier of velocity gradient information, or does the texture gradient itself provide information that reduces the ambiguity of surface definition?

Additional psychophysical research using simulated texture surfaces in motion is clearly needed. The basic research could be conducted with displays produced by motion-picture or video-disc animation. The stimuli would be variously curved and slanted surfaces moving toward or away from, parallel to, or obliquely to the observer. A major independent variable would be the relationship between the texture gradient and the velocity gradient. The two gradients could be made to provide reinforcing or contradictory information, and the relative weight that the observer gives to these two gradients in making various psychophysical judgments could be assessed. Of particular interest would be any differential effect that these two gradients have on judgments of degree of surface slant or curvature as compared to judgments of direction of slant or curvature. For example, the velocity gradient might serve as an indicator of degree of surface slant, but the observer's accuracy in judging which part of the slanted or curved surface is the closer might depend on the texture gradient.

The type of research outlined above would be useful in determining whether texture should be introduced into CIG displays, and what the specifications for this texture should be. If the texture elements serve only as carriers of velocity gradients, the texture gradients may not need to be accurately simulated. Recognizable texture elements may not be necessary, and symbolic texture elements may be sufficient. If, on the other hand, the texture gradient is itself of importance, then questions of element size and recognizability would need to be addressed. The key question is: Are symbolic texture elements and approximate texture gradients sufficient, or is accurate simulation of element size, gradients, and recognizability necessary? The answer to this question will have a major impact on the cost and increased complexity of CIG displays that would result from adding texture.

4.1.3 Shadows

It should be possible to use appropriate shadows to reduce the ambiguity of surface definition in CIG displays. Shadows should be especially useful for reducing ambiguities in surface elevation, slant, and curvature. In theory, the shadows created by directional illumination are a rich source of information to a moving observer. Two possible sources of viewer information are the relative motion between the object and its shadow and the different shape transformations that the object and shadow undergo as the viewer moves.

The value of shadows is dramatically illustrated in the space shuttle sequences, produced by an Evans-Sutherland system, and in the well-known perception demonstration that upside-down viewing of a photograph with strong shadows can reverse the apparent curvature of the photograph's surface features. The research on the effectiveness of shadows in surface perception is extremely limited. The few studies available concern shadows that do not change dynamically with changes in the observer's viewpoint; i.e., the stimuli are either still photographs (Hess, 1961; Yonas, Goldsmith, and Hallstrom, 1978) or moving objects on which fixed shadows have been painted (Cross and Cross, 1969).

Research is needed on the effectiveness of shadow for increasing the accuracy of judging surface elevation, slant, and curvature in dynamic scenes. Some preliminary research with static scenes would be useful both in developing response procedures for the dynamic scene research and in establishing baseline data against which the results with dynamic scenes could be compared. The need for this preliminary research with static scenes is due to the extreme paucity of data on shadow effects in the perception literature, as contrasted to an adequate amount of data on texture effects in static scenes.

There are at least three shadow conditions that should be considered in both static and dynamic scenes, and a fourth condition that is applicable only to dynamic scenes:

1. No shadows
2. Correct shadows for the expected direction of illumination
3. Shadows corresponding to the reverse of the expected direction of illumination (analogous to the upside-down photograph example)
4. Shadows that do not change dynamically with the observer's viewpoint.

The judgments of interest would include the height of surface features above the ground plane, slant of surface planes, and surface curvature. Since cast shadows are likely to affect judgments of the altitudes and velocities of the pilot's and other aircraft, these judgments should also be studied.

This research would provide a basis for assessing the value of modeling the direction of illumination and introducing cast shadows in CIG displays. It should also provide a basis for determining the importance of accurate, dynamic changes in these shadows. An alternative approach would be to add shadows that do not change dynamically with the observer's viewpoint. These shadows would probably be somewhat valuable in reducing surface ambiguities, and they would be less costly than dynamically changing shadows. On the other hand, because shadows that do not change appropriately with changes in viewpoint are likely to result in illusory perceptions of direction of motion (Cross and Cross, 1969), a choice between no shadows and dynamically changing shadows may be necessary.

4.1.4 Specular Reflection

There has been virtually no empirical or theoretical analysis of specular reflection's role in perception. Thus, the research should start by defining, on a priori considerations, the perceptual tasks and piloting activities that might possibly be affected by specular reflections. The analysis should also consider how specular reflections might interact with other perceptual cues, and how the importance of specular reflections might be increased or decreased by the special properties and constraints of computer-generated imagery (e.g., limited resolution and limited scene complexity). This first step will define the range of experiments which should be undertaken and should provide some indication of priorities. This step needs to be carefully conducted so that too many possibilities are not overlooked.

The goal of the next part of the research is to establish the importance of specular reflection, on its own and in interaction with other cues, in the performance of basic perceptual judgments. The research can be conducted in the laboratory, but would be best done using computer-generated imagery of the type used in simulators.

The major independent variable is the presence or absence of specular reflection. However, since interaction with other cues is of interest, the other cues should be manipulated as independent variables. These other variables might include texture, aerial perspective, shadows, and various degrees of scene complexity.

The dependent variables should include measures of accuracy for perception of distance (absolute and relative), movement (of observer and other objects), orientation and composition of surfaces, and detection and recognition of distant objects.

Another part of the research seeks to establish the importance of specular reflections with respect to a representative set of piloting activities. This work would best be accomplished in a simulator.

The independent variables for this research are the same as those described above for testing basic perceptual skills. The dependent variables should be measures of pilot performance on such tasks as low- and medium-level course navigation, low and medium tactical maneuvers (including aerobatics), air-to-ground target acquisition and weapons delivery, air-to-air target acquisition and weapons delivery, and landing. In this phase of the research, it would also be important to measure how user-acceptance is affected by the presence or absence of specular reflections.

4.1.5 Flatness Cues

Current CIG displays provide several cues to image flatness which may interfere with perceiving the displayed scene as three-dimensional. Instead, the display may tend to appear in the plane of the monitor screen. If these flatness cues are present, the perceived shapes, sizes, and relative velocities will deviate from those intended in the simulation. This deviation will be in the direction of the projected shapes, sizes, and relative velocities.

The visibility of the monitor frame is one flatness cue that could be virtually eliminated. A second cue, visibility of the raster lines, could be minimized. It is probably infeasible to eliminate the third cue, binocular vision, because to do so would require either major technological changes to provide accurate disparity information or the use of monocular vision during training. It is important to determine the seriousness of flatness cues as a limitation in CIG displays because the first two cues could be eliminated or reduced if an improvement in training were expected.

The appropriate research would consider how flatness cues affect the perceptual judgments involved in pilot training. These judgments would include those of surface slant, object size and distance, and the observer's velocity relative to the display. All three cues should be studied: the presence or absence of a visible frame around the display, the presence or absence of visible raster lines, and the use of monocular vs. binocular vision. Although the effects of the last variable would not have immediate implications for CIG design changes, they would be useful for comparison to the effects of the first two variables and for predicting the residual flatness perception in CIG displays that might be expected after eliminating the first two flatness cues. Other than a well-known study by Schlosberg (1941), almost no research has directly concerned the effects of flatness cues on depth perception. Flatness cues are discussed by Braunstein (1976, chap. 1).

4.1.6 Perceived Self-Motion

Most CIG systems do not produce a strong impression of self-motion. Recent perceptual research demonstrated that an impression of self-motion can be induced entirely by visual stimulation, and that this visually induced perception of self-motion dominates conflicting information from other sensory systems. A combination of central and peripheral stimulation was found to effectively induce perceived circularvection if enough moving texture elements were present (Brandt, Wist, and Dichgans, 1975). Peripheral stimulation was found to be both necessary and sufficient for perceived linearvection in either the up-down (Johansson, 1977) or the forward-backward (Lee and Lishman, 1975) direction. This research suggests that some combination of peripheral stimulation and moving texture elements in the central field may be necessary and sufficient to induce an impression of self-motion. (This suggestion is also supported by informal observations of a strong self-motion impression produced by a simulator using a wide-angle, motion-picture display that provided both texture and peripheral stimulation.)

Research is needed to determine the importance of visually induced perception of self-motion in CIG displays. The relevant questions concern the immediate effects of perceived self-motion on the perceived realism of the simulation and on velocity judgments in the simulator. It would be useful to consider the possible tradeoff between adding texture to the central field and providing peripheral stimulation. Initial research might elicit judgments of realism, perceived self-motion, and approach and landing speed in the presence of combinations of varying levels of texture in the central field and the presence or absence of peripheral stimulation.

The parameters of the peripheral stimulation to be tested (eccentricity, field size, etc.) can be obtained from existing literature. The relationship between the effectiveness with which self-motion is visually induced and the acceptance of the simulation would also be of interest. Finally, the relationship of visually induced motion perception to mechanical motion systems should be considered since recent research (Lee and Lishman, 1975) indicates that visual information overrides proprioceptive information. An effective system for visually inducing self-motion perception might reduce the need for mechanical motion systems. The perceived realism of motion simulation should be investigated using combinations of optimal visually induced perception of self-motion and mechnical systems. In this way, the conditions (if any) under which the addition of proprioceptive information to visual systems improves pilot perception and performance can be determined.

4.1.7 Update Rate

Although most state-of-the-art CIG systems are capable of updating at the refresh rate (usually 60 frames/sec), slower update rates are currently used, even in some new systems, to increase the number of edges that can be displayed. It is known that refreshing at a multiple of the update rate can result in the perception of multiple images. For example, a rapidly moving spot in a display updated 18 times/sec and refreshed at 54/sec is perceived as three distinct spots moving together (Braunstein and Coleman, 1966). This perceptual multiplication of images can be expected to decrease the display's realism. It also provides a cue to velocity that is not present in direct vision: The spatial separation of the perceived images of a moving spot is a function of that spot's velocity. Thus, if one runway edge light is perceived as two lights, for example, the perceived separation of the lights provides an artificial cue to landing speed.

Since this limitation does exist and can be eliminated, the issue of interest is the tradeoff between accepting this limitation and the additional computing load or reduced number of edges that its elimination would cause. Some system designers have accepted the presence of perceived multiple images in order to increase the number of displayed edges for a constant computing capability. To objectively evaluate such design decisions, research is needed to determine how detrimental multiple images are to training.

The required research would use comparable displays that differ in update rate (30/sec vs. 60/sec) but are constant in refresh rate (60/sec). Judgments of realism and trainee acceptance should be obtained for the two update rates. The most important issue is how well training transfers from displays at each update rate to direct vision. To assess the probable effects of update rate variations on transfer of training without using actual flight time, transfer of training in making accurate velocity judgments could be assessed by using displays with either the same or different update rates. That is, subjects trained to make velocity judgments at the 30/sec or 60/sec update rate would be subsequently tested at the same or the other rate. If there is a significant decrement in going from the 30 condition to the 60 condition, it would be reasonable to suspect that cues are present in the former that do not transfer to the latter, and that a similar decrement might arise in going from the 30 condition to direct vision. The nontransferring cues might then be investigated in more detail to determine whether they could be reduced without increasing the update rate.

4.2 AREAS FOR ALGORITHM RESEARCH

Several relevant areas for algorithm research are important to both current and advanced CIG simulation technology. The first area needing research is smooth shading methods, since the Gouraud shading used since 1971 is perspectively inaccurate. The second area requiring investigation is textured shading, since there is some psychological evidence to indicate that simple tonal gradients can be just as effective as the several approaches to textured shading that have many variable parameters associated with them. Until work on perspectively valid smooth shading and some known textured shading approaches is performed and compared, important information will be lacking.

The third area for research is general reflection. While present CIG simulators rely totally on diffuse, Lambertian reflection, the need for more scene complexity in the form of edge capacity has been expressed. However, general specular reflection can add significant display complexity without edges, and the reflection algorithm (unlike edge processing algorithms) is truly linear in complexity without buffer requirements.

The fourth research area concerns shadows, since they are difficult to compute for polygon-based systems. The fifth and final area concerns contrast management. There is psychological evidence (e.g., Cornsweet's illusion) that processing can produce the perception of high contrast without the corresponding need for high energy output on the display.

4.2.1 Smooth Shading

If Gouraud shading has significant negative impacts, they need to be identified. Gouraud shading is the common algorithm for smooth shading, even though it is perspectively invalid (Subsection 3.2). The inverse range shading method is perspectively valid but involves more computation. Thus, analyses and tests of the psychological impacts of these two smooth shading methods are needed.

The analysis of smooth shading methods is based on perspective geometry and human spatial perception. The geometry is simple to compute in both scene and screen spaces, but the perception is not easily analyzed for general circumstances. At issue are the basic mechanisms used by the human to perceive the scene (e.g., flat surface, source of perceived gradient).

The experimentation with shade application methods should involve dynamic scenes in order to provide the types of displays used in flight simulation. Otherwise, false conclusions based on static displays may occur. Subjects can be shown the displays and asked what they saw, what motion occurred, etc. The displays can be a single flat surface with either Gouraud or inverse range shading along some motion path. The motion paths might include straight lines, with and without rotation, and hyperbolic descent. Different geometries need to be tested for sensitivity to any improper perceptions due to Gouraud shading. These tests and their analysis can be the starting point for a family of experiments. By designing experiments that present the test subjects with dynamic scenes shaded according to the different shade application methods, the perceptual performance resulting from the different methods can be determined.

4.2.2 Textured Shading

There is a need to predict the relative merits of tonal gradients and texture patterns both separately and together. Although several efforts have been started to analyze and develop texture methods, psychological evidence indicates that simpler tonal gradients provide strong motion and distance cues which may be as strong as those provided by texture. Thus, analyses and tests of the psychological impacts of these two methods are needed.

The analysis involves perspective geometry and human spatial perception. The analytical bases are the same as needed for evaluating Gouraud shading (Subsection 4.2.1). The difference is in the evaluation of texture. The important variables used in texture are element size, density, and hierarchies. There are several very different approaches to textured shading such as texture tiles, bombing patterns, periodic functions, and random generators. Analyzing and controlling the variables in each texturing approach is important.

The experimentation with smooth and textured shading should proceed much as described in Subsection 4.2.1. Dynamic motion sequences of 5 sec or more can be shown to subjects who are then questioned on what the scene consisted of, what motion path they took, and other relevant aspects of distance and motion. The motion paths should be simple; e.g., straight lines with and without rotation and speed changes, hyperbolic descent to the ground plane, or "S" turns. The scene should be a simple, single ground plane surface for this research. Thus, all the subject sees is the shading method on the surface and the horizon. This approach has worked very well because no other cues are available to confuse results.

The different texturing methods should be compared to tonal gradients for accuracy of cues.

4.2.3 Shadows

Although the inclusion of shadows can make significant differences in human perception, shadows are hard to compute and consume valuable edges in polygon-based CIG simulations. However, other approaches to CIG simulation may permit shadows to be used within system constraints.

The analytic and experimental work with shadows should deal with Defense Mapping Agency terrain. This type of scene is difficult to model and thus represents a limit on simulation performance. The use of shadows may significantly improve the human perception of terrain in advanced simulation. Standard test procedures should be used to study terrain displays with and without shadows, including the motion paths developed for the research areas described above. The subject views a 5-second motion sequence and is asked what the scene consisted of, what motions occurred, and whether shadows helped interpretation. This procedure should be used for gentle and rough terrain and high and low scan angles.

4.2.4 General Reflection

The use of nondiffuse, non-Lambertian reflection could lead to the need for fewer edges and to better human perception. Because diffuse reflection yields featureless surfaces without internal structure (or even visible boundaries in some areas), unrealistic and cartoonish imagery results and there is an absolute reliance on edges to carry scene display information. The several reflection methods that can be used instead of diffuse reflection can produce realistic surfaces that appear to be dynamic and have highlights (i.e., specular) that follow the moving observer around the scene.

The analyses and experiments parallel those described in Subsections 4.2.1 and 4.2.2. A single ground plane with or without texture should be displayed with a general bidirectional reflection mode. The standard motion sequencer should be used. All experimental results obtained for the different algorithms--1) Gouraud vs. inverse range shading, 2) attenuation gradient vs. various textures, and 3) one general reflection model vs. another--should be compared to determine which combination(s) of algorithms produces the best perceptions.

4.2.5 Contrast Management

Display devices have limited energy output which results in limited dynamic range. The use of contrast management to maintain the display energy requirements within device limits has significant benefits. There are experimental results--e.g., Cornsweet's illusion (1970)--which indicate that differential filters reduce the energy output requirement for a given contrast perception.

The analysis involves human retina, lateral geniculate, and striate cortex physiology. It seems that the response of the visual system to imaged light is the Laplacian of the Gaussian distribution involved with the image. Given this information, an attempt might be made to devise special filters that are blind to the visual system and reduce contrast.

The experimentation based on these analyses involves dynamic displays of standard patterns such as bars, crosses, circles, hinges, and checkerboards. If these displays produce good results, live and simulated imagery should be tested. Unlike the four research areas discussed above, this work may not lead to relevant algorithms; however, it does offer the opportunity to significantly improve CIG displays.

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Appendix A

CONSULTANT INTERVIEWS

This appendix presents detailed reports of interviews with perceptual-knowledge experts. These reports were written by members of the program. The experts interviewed include:

1. Conrad Kraft and additional members of the Crew Systems Division, Boeing Aerospace Company
2. Herschel Leibowitz, Pennsylvania State University
3. Allen Pantle, Miami University
4. Tarow Indow, University of California at Irvine
5. Walter Gogel, University of California at Santa Barbara.

A.1 INTERVIEWS WITH BOEING PERSONNEL (19-21 April 1979)

A large number of issues relating to perceptual aspects of CIG displays were discussed with Dr. Conrad Kraft and other Boeing personnel. The points brought out in the discussion are organized into three categories: CIG problems that remain in state-of-the-art systems, issues for the model-builder, and research areas that are expected to contribute to improvement of CIG displays.

A.1.1 CIG Problems

Image Doubling

Two conditions are necessary for image doubling to occur. One is that the update rate must be slower than the field rate, i.e., a given object's position is updated or changed only on every n^{th} field, where $n>1$. Second, the angular velocity of the object must exceed a critical value. For commercial aircraft, objects on the ground (such as runway lights) exceed this velocity during landing, takeoff, and even short radius turns on the ground. The critical velocity would be exceeded more often in tactical aircraft. The problems caused by this phenomenon are reduction of realism, negative transfer because artificial cues to velocity are given, interference with visual recognition and identification tasks, and possibly the generation of false motion information through strobe effects.

A possible perceptual analysis is as follows. The odd fields show the object moving smoothly through the field of view, i.e., position is changed at a uniform rate from one presentation to another. The result is a percept of a single, smoothly moving object. The even fields act similarly, generating a second percept of a single, smoothly moving object. However, these two percepts are not fused into one because there is not commensurate motion of the object from the first field to the second. To fuse the two percepts, it would be necessary to perceive a single object moving, halting, moving, halting, etc., across the field. Instead, the visual system organizes the information as two separate but smoothly moving objects. The repeated move-halt pattern can be treated as the result of a smooth movement component and a sawtooth component having a fundamental frequency equal to the frame rate. The visual system treats the smooth component as representing motion, but interprets the sawtooth component as representing two spatially distinct objects.

Flat Earth Model

Because current data bases use a flat (rather than a spherical) earth, one result is that the distance between the end of a runway and the horizon is distorted. That is, the separation is greater than would be the case with a spherical earth. The effects of aerial perspective would also be distorted. Unknown effects on the perception of distance and orientation may be resulting from the artifactual flatness and distorted position of the horizon.

Color Temperature Changes

Present systems do not represent the substantial changes in color temperature of the illumination which occurs at dawn and dusk. Perhaps more important, when the sun angle is low, there are marked color temperature changes depending on whether flight is into or away from the sun. These changes might be particularly helpful in low-altitude tactical visual flight guidance.

Lack of Directional Sun

Visibility, glare, and light scattering effects change drastically as flight heading is altered with respect to the sun. These effects, which are not represented in present systems, are probably very important for certain kinds of tactical training because they can be exploited by a pilot (or his enemy) to prevent visual detection and recognition.

Other CIG Problems

An algorithm is used that causes displayed lights to grow in an area up to a maximum size. An illusion of shrinkage occurs when the light size reaches its maximum and is held constant.

Saturated colors may make object detection too easy. The view was expressed that more edges may be needed to make detection more realistic.

Color matching for multiple-monitor displays was considered to be nearly impossible due to peculiarities in picture tubes and driving characteristics. If two monitors are adjusted so that color matches are satisfactory at one luminance, the matches may be unsatisfactory at other luminances.

The distance at which runway markings become visible was considered critical to performance. In the simulator, this distance varies with luminance settings, thus making realistic simulation difficult.

Aliasing problems may serve as distractors in air-to-air and air-to-ground tasks. The pilot's attention may be attracted to some area of the display because of an aliasing problem, thus causing a decrement in detection of a target elsewhere in the display.

A combination of fading and blending was considered to be a probable solution to the CIG problem of making lights gradually disappear.

A.1.2 Issues for the Model-Builder

1. Should the maximum visibility be limited, perhaps to 40 miles?
2. Should there be preset configurations of atmospheric conditions from which the instructor would select, rather than separately variable parameters?
3. There seemed to be general agreement that a sun model would be useful to provide realistic shadows and some simulation of glare effects.

4. In developing the final data base for a new simulator, it was necessary to pare a larger available data base to a manageable size. Two criteria were used, one of which was the maintenance of realism, especially through the inclusion of specific features needed for training purposes (e.g., a specific building that pilots used as a cue for turning). The second criterion was the maintenance of essential visual cues, which was sometimes accomplished with artificial features rather than with features that attempted to match the real world.
5. Enough detail is needed in the far periphery and forward to provide relative motion cues. Farther out, the rectangular pattern of the runway with some differentiation should be sufficient. Regular patterns in the far periphery or straight ahead should be avoided as these can cause perceived movement reversals.

A.1.3 Suggestions for Needed Research

1. Present data on contrast sensitivity functions seem to be adequate in form. A different format is not suggested.
2. The effects of curved and flat horizons on judgments of distance, shape, and orientation. Flight performance tasks do not need to be used as measures.
3. Effect of the size of the field of view on the accuracy of motion perception, perception of self-motion, and performance of various flight and gunnery tasks.
4. Questions about thresholds for motion perception and linearvection based on motion displays presented to the far periphery include a) What are the latencies for these perceptions? and b) Are some pilots more sensitive than others to movements in the far periphery?
5. Other questions about motion perception include: What individual differences exist in pilots' use of vestibular vs. visual motion cues and in resolving peripheral vs. central motion perception conflicts?
6. The effect of update rate on the accuracy of motion and velocity judgments, perception of self-motion, and performance of detection and recognition tasks involving objects with moderate and high angular velocities.
7. Size and contrast thresholds for peripheral vision. How much detail is needed for adequate perception of orientation and motion? (See Leibowitz interview, Subsection A.2.)

8. Effect of blur and reduced resolution on performance of various flight and gunnery tasks. Important for setting display specifications and for evaluating anti-aliasing algorithms which reduce resolution.

9. Additional information is needed on the detection, recognition, and orientation of distant air and ground targets. What are the real detection and recognition ranges? What stimulus properties (e.g., spatial frequency components) are actually used? This information is needed for fitting CIG systems to specific training requirements.

10. Assessment of individual differences with respect to detection and recognition performance, use of peripheral vision, and perception of motion. An important question is whether pilots, as a class, tend to differ from the general population with respect to these characteristics.

11. A need was expressed for a measure of scene complexity.

12. There is a need for transfer-of-training studies. The same perceptual and performance measures should be taken in actual flight and in simulators.

13. Can a need be demonstrated for the use of color?

14. What is the optimum tradeoff between resolution and field of view?

15. For detection and recognition tasks (e.g., air-to-air combat), data are needed on the recognition of attitude changes of a small spot, possibly produced in the simulator with inserts.

16. Research is needed on the importance of using the side windows.

17. Defining the side of a hill might be improved by the use of shadow, surface shading, and rounding of contours. Research is needed on whether texture would be helpful.

18. Some of the needed research could use perceptual measures (e.g., magnitude estimates) instead of transfer of training.

A.2 INTERVIEW WITH H. LEIBOWITZ (28 April 1979)

Professor Leibowitz discussed the stimulation required by the ambient system, factors influencing accommodation, the interaction of the vision system and the perception of motion, and the impact of size and shape constancy on CIG displays. In addition, Professor Leibowitz stated that stereo displays, color displays, and the inclusion of chromostereopsis are not necessary for flight simulators.

A.2.1 Peripheral and Ambient Vision

Much recent evidence suggests we have two visual systems: 1) the focal system, which primarily uses the central part of the visual field and provides information about fine detail and form, and 2) the ambient system which uses the peripheral part of the visual field and provides information about motion and spatial location and orientation. Because many problems in flying involve orientation in space, it is important to provide adequate stimulation to the ambient system. However, it is probably not necessary to provide detailed information. For example, circularvection--the perception of self-motion produced by rotating the visual field--is unaffected by severe blurring of the retinal image or by large variations in luminance (Leibowitz, Rodemer, and Dichgans, 1979). Stimulation of the ambient system probably requires a large field of view but little detail.

A hypothesis about night-driving accidents is relevant to simulator displays. At night, the ambient system is adequately stimulated despite low illuminances. The driver receives adequate information about his location and movement in space and therefore feels confident. However, because the low illumination hampers the focal system, the driver does not receive adequate information about obstacles, road defects, and other features which cause accidents. Although the visual display in a simulator may provide enough information to the ambient system to produce a feeling of realism and confidence, adequate detail for the focal system and for performing the tasks it mediates may be lacking. Thus, a feeling of good realism is not an adequate assessment.

A.2.2 Accommodation

In the absence of appropriate stimulation, accommodation seeks a resting state which varies from one individual to another. Although the range of variation is large, the resting state for the majority of persons tested is within one meter. The resting state is measured in the dark; however, individual accommodation in certain other situations is highly correlated with the dark state. These other situations include night settings and empty-field situations (such as a pilot encounters when in the air).

In other situations, accommodation is always a compromise between the dark focus and the accommodation appropriate for the object fixated. The variables which control accommodation have not been completely worked out. However, as illumination and contrast increase, the compromise moves from the dark focus towards the locus of the object fixated. For high contrast patterns, Owens found that the intermediate spatial frequencies (those at the peak of the contrast sensitivity curve) more effectively control accommodation than do either high or low spatial frequencies. Peripheral stimuli (such as the edge of the cockpit window) play a role as well. Thus, accommodation may be viewed as a three-way compromise among the individual's dark focus, the locus of the object fixated, and the locus of peripheral objects. Stress also appears to play a role.

Some attempts have been initiated to improve visual performance at night be providing the viewer with an individual optical correction equal to one-half the dark focus. The results appear promising.

The finding by Owens (1976) that the middle spatial frequencies most effectively stimulate accommodation rejects an earlier speculation that the absence of high frequency components from a CIG display might limit its capacity to stimulate accommodation. It would appear that the major problem may be quite the opposite; i.e., if the raster is resolvable, it may provide a stimulus for accommodation to distant objects which would be absent from the normal cockpit scene. Thus, distant objects and aircraft would be detected and recognized more quickly in the simulator than in an actual aircraft.

A.2.3 Perception of Motion

Perception of motion involves interaction of the visual and vestibular systems. However, in many cases it may be cheaper to produce perceptions of motion by means of visual displays than by means of mechanical motion. Furthermore, certain kinds of information are signaled only by the visual system (e.g., constant velocity motion is not signaled by the vestibular system).

A.2.4. Size and Shape Constancy

Size and shape constancy refer to the ability to accurately perceive an object's size and shape regardless of the viewing distance or viewing angle. This ability provides an index of complex perceptual performance with respect to the judgment of size, distance, shape, orientation, and (sometimes) motion.

Blurring of the retinal image and reducing the stimulus luminance and viewing time do not affect size constancy, although reducing the size of the visual field does. These facts support the hypothesis that size constancy is mediated by the ambient visual system. They also suggest that, in the visual simulator, the size of the field of view is more important than the amount of detail for the kinds of visual judgments represented by size constancy. On the other hand, blurring and the reduction of luminance and viewing time do reduce shape constancy. These latter facts suggest both that shape constancy is mediated by focal vision and that, with respect to display systems, good resolution and detail are important to the perception of shape and orientation.

A.2.5 Stereo Displays

Leibowitz has written a report showing that the information presented in a stereo display can also be obtained from a nonstereo display--without the extra expense and loss of resolution which stereo entails. Thus, stereo displays do not appear worthwhile.

A.2.6. Color

Leibowitz believes that color adds little essential information. There may also be a report on this topic. Leibowitz suggests contacting Dr. Milton Whitcomb.

A.2.7 Chromostereopsis

Leibowitz believes that this phenomenon is not critical for flying situations and flight simulators. Since the effect is large only when the viewer's pupils are small, in a natural viewing situation with natural pupils, the effect is small.

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A.3 INTERVIEW WITH A. PANTLE (7 May 1979)

Professor Pantle discussed the masking effect of the raster pattern, the effect of update rate on the perception of motion, the correlation between spatial frequency and motion detection, and the correlation of dynamic texure.

A.3.1 Masking

Masking refers to the fact that the presence of one stimulus or one stimulus component may interfere with the perception of a second stimulus or component. The phenomenon is relevant for two reasons. First, to the extent that the raster is resolvable, the raster structure may interfere with the perception of objects represented in the display. A knowledge of masking is needed for selecting the optimal characteristics of the raster and for ameliorating any masking effects of the raster by appropriate modifications of the data base. Second, masking is the psychophysical research area most relevant to the effects of "clutter" on detection and recognition. A knowledge of masking is needed to optimize clutter effects while still remaining within the limits placed on the amount of detail possible in CIG displays.

The basic findings on masking are summarized in a technical report by Pantle (1974). There have been no fundamental advances since then. However, Sansbury and Legge recently did some important work, and their results are presumably now being prepared for publication.

To a large extent, masking can be treated as filtering. The effect of the mask is equivalent to filtering out or selectively attenuating components which are similar to the mask in orientation and spatial frequency (or orientation, size, and position). Ginsberg's work is highly relevant; he has looked at the effects of various kinds of selective filtering on the perception of complex scenes and patterns. His work is summarized in an Air Force Technical Report which is presently being prepared for publication. However, Ginsberg does not deal with the dichotomy between sustained and transient mechanisms (see Breitmeyer and Ganz, 1976; Tolhurst, 1975), nor does he deal with dynamic scenes. With respect to the latter, high frequency masking stimuli may interfere with the perception of micromovements.

A.3.2 Update Rates

Good apparent motion can be seen with low update rates. However, a motion aftereffect is not produced if the object moves too far from one presentation to another, i.e., if the update rate is too low. The lack of adaptation is important with respect to simulators. A low update rate might leave the pilot unprepared for the effects of adaptation which occur in the natural situation. The lack of adaptation also suggests that the mechanisms being stimulated at low update rates are different from those at high update rates.

In addition, a high update rate is needed if micromovement is to be perceived. Micromovement is the movement of a small object within a large cluster, e.g., a tank within a group of tanks. The critical interval between presentations is 50 msec or even less (see Shepard and Metzler, 1971; Pantle and Picciano, 1976). Further, the capacity to perceive a complexly or randomly textured surface as a segregated entity depends on high update rates (Persik, Hicks, and Pantle, 1978). This fact is relevant to the use of textures to define surfaces in CIG displays.

Pantle believes that the basic mechanism of movement perception responds to small displacements presented within short periods of time. The displacements must be 30 min of visual angle or less, and the time between presentations must be 50 msec or even less if the basic mechanism is to be activated. Pantle believes that the motion perceived at slower update rates is mediated by a higher-order, learned mechanism. A 30-Hz update rate has 33 msec between presentations. Pantle's data suggest that this is a borderline interval, sometimes adequate and sometimes not.

A.3.3 Contrast Sensitivity to Moving Patterns

One source of information on this topic is the literature on the detection of gratings which flicker in counterphase. Such a grating is equivalent to two moving gratings. There is a correlation between the spatial frequency of a component and the rate of motion at which it is best detected (Watanabe, et al., 1968; Pantle, 1970). One consequence of this correlation is that as the velocity of an object changes, the spatial frequency components that are important for the object's detection and recognition will also change (Pantle, 1970; Breitmeyer, 1973).

A.3.4 Texture

A moving, random texture pattern is perceived as a single, moving entity or surface only if it is quite noise-free. Experiments indicate that if the correlation between the pattern at successive presentations is less than 0.95, the pattern will not be perceived as a segregated entity.

A.3.5 References

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A.4 INTERVIEW WITH T. INDOW (22 February and 29 March 1979)

The discussions with Professor Indow centered around the question of how, ideally, the colors in a CIG display should be determined and calibrated. He made the following recommendations:

1. Five to seven colors should be selected from the real-world scene as the colors to be used in the matching procedure. These colors should be selected according to their importance in the performance of the task of interest. For example, the selection of the colors to be matched when the task of interest is landing might be determined by asking pilots what colors are most important to them in performing this task. (This question would be asked in terms of environmental features--e.g., the color of the runway surface or of various lights--rather than in terms

of color names.) The five to seven colors selected as standard colors should cover the entire color space, in addition to being of importance in the task of interest.

2. Psychophysical matches, rather than matches based entirely on physical measurements, should be used to match the perceived colors in the CIG display to the perceived real-world colors.

3. The psychophysical matching procedure should not rely on the observer's memory of the real-world colors, since colors tend to be remembered as more saturated than they actually are in the real scene. Instead, the following general procedure should be used:

   a. Color matches should be made under varying conditions of illumination in the situation to be simulated (e.g., during an actual aircraft landing). The observer should match the directly perceived colors to color chips, such as the Munsell chips.

   b. The observer would set the colors in the simulator to match chips of the same color, using a standard procedure for setting up the colors in the CIG system and for calibrating monitors.

4. Specification Systems: With respect to discrimination and just-noticeable differences, the Commission Internationale de l'Eclairage (CIE) Uniform Color Scale is useful for practical applications, except perhaps in the violet. However, for suprathreshold differences (such as those involved in judgments of similarity and realism), Munsell specifications are more useful. It is important to observe the differences between matte and lustre finishes.

5. Shading: Objects in the real world are not uniformly colored; rather, there is considerable variation from one part of a surface to another. This variation arises mostly from nonuniform illumination. Indow believes that it is more important to provide some shading than to get the basic colors right. Lack of color gradients is a major problem with present displays.

A.5 INTERVIEW WITH W. GOGEL (9 February 1979)

Professor Gogel discussed a number of aspects of distance perception:

1. Because at high altitudes there are few cues to distance in the actual flight situation, distance is probably often misperceived (underestimation is most likely).

The relationship between errors in distance perception and the accompanying errors in size perception is delineated in the literature on the size-distance invariance hypothesis.

2. One distinction which is important when studying the literature is the difference between reported and registered distance. A pilot must learn to correct registered distance, and this process may be involved. One task of simulators might be to teach pilots to use cues, such as resolution criteria, which are not usually used in perception.
3. When distance cues are minimal, two perceptual tendencies become important. One is the equidistance tendency (objects tend to be seen at the same distance), which may cause a runway to appear tilted upward. Henry Mertens has studied the problem of judging the orientation of a runway on approach. The second tendency is the specific distance tendency (objects tend to be registered as being at a specific distance rather than being processed as indeterminate in distance).
4. Outline gradients and outline perspective appear to be more important than texture. The relevant experimental work is by R. Freeman and there was an interesting exchange between Freeman and Flock. The existing work has been mostly with static scenes and thus does not really assess the importance of accretion and deletion of texture in dynamic scenes. In a reduced cue situation, texture may contribute to the equidistance tendency.
5. One issue is how much peripheral stimulation is needed to produce a full perception of motion. The experimental work in this area is by Johansson and his colleagues.
6. There is evidence that the perceptual effects of shadows depend on the assumed location of the illumination source. The older work in this area is by Gogel and Hess on chicks; the more recent work is on human infants. Sources to look at are I. Rock's text on perception, and the developmental text by Cohen and Salapetek.
7. Lew Harvey published a study on how changes in the apparent size of approaching lights affect distance judgment.
8. Aerial perspective may provide some relative distance information, but not absolute distance information.
9. In dynamic scenes, the changes in perspective and shape over time may provide a great deal of information.

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Appendix B

LITERATURE SUMMARIES

This appendix contains summaries of the literature on perceptual knowledge that relates to the limitations identified in Section 2. The summaries are arranged to parallel the major topics delineated in that section. Each summary briefly describes the work and results reported in the document/article, and highlights the applicable implications for CIG.

The summaries are arranged as follows:

B.1 Contrast Management and Aerial Perspective .... p. 106
B.2 Resolution .... p. 149
B.3 Dynamic Range .... p. 162
B.4 Directional Illumination Effects .... p. 179
B.5 Raster Effects .... p. 184
B.6 Color .... p. 196
B.7 Level of Detail .... p. 203
B.8 Surface Definition .... p. 217
B.9 Perceived Flatness of the Display .... p. 278
B.10 Minimal Scene Content .... p. 283
B.11 Size and Continuity of the Visual Field ...... p. 302
B.12 Hybrid Display and Update .... p. 320

Subsection B.13, Bibliography, provides additional sources that were not included in the summaries.

B.1 CONTRAST MANAGEMENT AND AERIAL PERSPECTIVE

Several CIG problems identified in Subsection 2.1 are grouped together because their amelioration involves more effective contrast management. Contrast management refers to controlling the visibility of an object by manipulating its physical contrast. A certain amount of this manipulation can be accomplished in the model or data base. Other manipulations require real-time computation as the object's distance or apparent size changes. Both strategies are intended to circumvent certain unrealistic percepts that result as objects approach the resolution limit of a display system. The perceptual and display characteristics that contribute to these problems are detailed in Subsection 2.1.

In brief, these problems may be summarized in the following way. When an object recedes into the distance, its angular subtense decreases and the object gradually disappears as the resolution limit of the eye is approached. However, in a video image the angular subtense of an object cannot be reduced below one pixel, a size that is two to four times larger than the resolution limit of the eye. As a result, perceptual distortion of the object occurs. However, since the resolution limit of the visual system partly depends on the contrast or intensity of the object viewed, a combination of the following methods can be employed to lessen the resulting perceptual distortions:

1. The contrast between an object and its surroundings can be kept low in the data base.
2. The object's contrast can be reduced as the square of the calculated viewing distance, once the one-pixel limit has been reached.
3. Aerial perspective can be simulated and the attenuation which it incorporates will serve to reduce contrast as a function of viewing distance.

Relevant psychophysical literature concerns visibility and brightness as a function of stimulus size and shape; contrast sensitivity as a function of size, shape, and spatial frequency; and the optical-neural spread functions of the visual system. Other relevant literature describes the contrast attenuation produced by the atmosphere which is required for the simulation of aerial perspective. The articles summarized in this subsection deal with these topics.

Barlow, H. B. Temporal or spatial summation in human vision at different background intensities. Journal of Physiology, 1958, 1958, 141, 337-350.

Key Words: Temporal and spatial summation

Increment thresholds have been measured in a retinal region 6° 30' from the fovea with test spots of varying sizes and durations superimposed on backgrounds of various intensities.

The total amount of summation (as measured by the ratio of lowest threshold quantity of light to lowest threshold intensity) decreases continuously as background intensity is raised. This decrease occurs in the photopic as well as the scotopic range.

The upper limit of complete temporal summation is decreased by increasing the area of the stimulus and by increasing the background intensity.

The upper limit of complete spatial summation is decreased by increasing the duration of the stimulus and by increasing the background intensity.

The increment threshold lies above the limit set by quantal fluctuations of the background light, except possibly for a single set of conditions: factors which might prevent attainment of the limit are suggested.

CIG Implications: Contrast thresholds are affected by the temporal and spatial summations of the human visual system which in turn are affected by the level of background illumination. Implementation of the suggested procedures for contrast management (see Subsection 2.1) depends on a knowledge of how these stimulus parameters affect contrast sensitivity. The present article contains a substantial portion of these data for a periodic stimuli.

Baron, W. S., and G. Westheimer. Visual acuity as a function of exposure duration. Journal of the Optical Society of America, 1973, 63, 212-223.

Key Words: Vernier acuity; exposure durations

Changes of visual acuity with exposure durations shorter than the critical duration for detection can be attributed to simple light summation. However, changes of visual acuity with longer exposure durations must be otherwise accounted for. This paper shows changes of photopic acuity with prolonged exposure durations, and considers several possible underlying mechanisms. The acuity threshold was found to decrease with exposure durations up to 400 ms and possibly longer. Thus, pupillary and accommodative fluctuations were investigated, as mechanisms concerned, but were found to have no effect on the phenomenon. A task-specific summation period was sought; however, no evidence for such was found. Also, similar results were found whether the presentation consisted of a single uniform exposure or two discrete exposures with some interval between.

CIG Implications: The reason for the decrease in visual acuity thresholds with longer stimulus durations is not well understood. Nevertheless, the phenomenon can be effectively exploited to control the appearance of displayed objects as a function of calculated viewing distance. If objects are "switched in" at or near threshold contrast when some critical distance is reached, their detectability should increase in a gradual and natural manner after they are first displayed.

Blackwell, H. R. Contrast thresholds of the human eye. Journal of the Optical Society of America, 1946, 36, 624-643.

Key Word: Contrast thresholds

Experimental data are presented representing approximately 450,000 responses made by trained observers under laboratory conditions. Contrast thresholds are presented for stimuli brighter and darker than their background and for two values of stimulus exposure. In each case, wide variations were studied in the parameters: stimulus contrast, stimulus area, and adaptation brightness.

CIG Implications: An extensive study on contrast thresholds that provides the basic data required for contrast management in terms of stimulus variables and individual variation.

Breitmeyer, B., and L. Ganz. Temporal studies with flashed gratings: inferences about human transient and sustained channels. *Vision Research*, 1977, 17, 861-865.

Key Words: Transient response; contrast sensitivity; spatial frequency

The temporal response properties of the human visual system to low and high spatial frequency gratings were investigated by two contrast detection threshold techniques. With the first technique the contrast threshold for detecting vertical sinusoidal gratings at spatial frequencies of 0.5, 2.8 and 16.0 c/deg was determined at exposure durations ranging from 20 to 400 msec. It was found that the critical duration, at and below which reciprocity between contrast and a nonunity power of duration holds, increased from roughly 60 to 200 msec as spatial frequency increased from 0.5 to 16.0 c/deg. The second technique involved subthreshold summation of two 10-msec flashed presentations of either a 1.0 or 10.0 c/deg grating. The stimulus onset asynchrony (SOA) separating the onsets of the two pulses varied from 0 to 210 msec. The results revealed that the subthreshold interaction of the two flashes at high spatial frequencies can be characterized by monophasic sustained excitation and inhibition; at low spatial frequencies, however, this interaction can be characterized by a multiphasic oscillation of excitation and inhibition superimposed on a monophasic excitatory-inhibitory interaction. The findings are related to properties of transient and sustained channels assumed to exist in human vision.

CIG Implications: Transient channels produced nonlinearities in the spatial and temporal sensitivity of the visual system that should be considered in the development of contrast management algorithms.

Breitmeyer, B., and B. Julez. The role of on and off transients in determining the psychophysical spatial frequency response. Vision Research, 1975, 15, 411-415.

Key Words: Vision; transient response

Two experiments were run to investigate the contrast sensitivity of the visual system to sinusoidal gratings of variable spatial frequency when onsets and offsets of their presentations, lasting about 500 msec, were either abrupt or gradual. In the first experiment, it was found that a presentation having abrupt onsets and offsets, relative to one having gradual onsets and offsets, increased the contrast sensitivity at low spatial frequencies but left unaltered the sensitivity at high spatial frequencies. This result is consistent with previous findings which indicate that visual channels preferring temporally transient simulation are predominantly tuned to low spatial frequencies. In a second experiment it was found that the increase in contrast sensitivity at low spatial frequencies is primarily due to the leading abrupt onset; i.e., at low spatial frequencies a presentation having an abrupt onset and gradual offset increased contrast sensitivity relative to a presentation having a gradual onset and abrupt offset. This result suggests that the spatiotemporal frequency response of the visual system, like its temporal or spatial frequency response, must be specified not only in terms of a modulation transfer function but also in terms of a phase response.

CIG Implications: In several simulator displays, objects appear to suddenly pop in or out of view as they reach the edge of the display. The results of this article indicate that abrupt onsets will produce a more unrealistic perception than abrupt offsets. Therefore, priority may be given to the stimulus onset in efforts to mitigate this problem.

Brown, B. The effect of target contrast variation on dynamic visual acuity and eye movements. Vision Research, 1972, 12, 1213-1224.

Key Words: Dynamic acuity; contrast

Contrast is important in determination of dynamic visual acuity (DVA). Reduced contrast produces decrement of performance because of two separate effects, one on static acuity and one on eye movement control. The effects of reduced contrast on eye movements for the experiment reported here are not marked, except at low contrast levels; decrease of target contrast produces increased latencies (for the initial eye movement latency and the subsequent saccadic movements) and a decrease in the final pursuit velocity of the eye movement.

In the present experiment the effect of contrast on eye movement control is masked by the compensation brought about by the increased size of targets presented. A study without the complicating effect of this increased target size would be of interest. An equivalence between the effects of reduced target contrast and increased target image velocity on DVA can be calculated. The data of the present paper allow the derivation of threshold sizes of targets with contrasts between 70 and 20 percent, moving with angular velocities from 0 to 90°/sec.

CIG Implications: An accurate simulation of real world relative contrast is important for increasing the degree of positive transfer to actual flight conditions in terms of eye movement control. Unnaturally high contrast in the display caused by the lack of aerial perspective and the veiling glare of the windscreen may not adequately prepare the pilot for the difficulties of eye movement control encountered under low contrast conditions.

Campbell, F. W., J. J. Kulekowske and J. Levenson. The effect of orientation on the visual resolution of gratings. Journal of Physiology, 1966, 187, 427-436.

Key Word: Spatial orientation

The effect of orientation on the contrast detection thresholds of sinusoidal gratings were measured for spatial frequencies between 1 and 35 c/deg. Contrast thresholds are higher for oblique gratings compared to either the horizontal or vertical orientations, and the difference is somewhat more pronounced at higher spatial frequencies. The orientation effect is attributed to neural rather than optical factors of the visual system.

CIG Implications: Provides basic data required to implement more effective contrast management as a function of stimulus orientation.

Duntley, S. Q., W. H. Culver, F. Richey and R. W. Preirendorfer. Reduction of contrast by atmospheric broil. Journal of the Optical Society of America, 1963, 53, 351-357.

Key Words: Atmospheric attenuation; aerial perspective

It is shown that the probability of receiving light from an object viewed through a turbulent atmosphere follows a normal Gaussian distribution. Furthermore, the root-mean-square angular deflection of the points of any object will be proportional to the square root of the object-to-observer distance. From relations of the type described in the examples it is possible to predict the apparent contrast throughout a given scene, provided the inherent contrast distribution, the optical air state, and the range of the target are known. The optical air state for a given condition of atmosphere can be measured by using a telephotometer and a series of long thin black bars of varying widths.

CIG Implications: Contains a portion of the basic data and procedures required for adding aerial perspective to simulator displays.

Farné, M. Brightness as an indicator to distance: relative brightness per se or contrast with the background? Perception, 1977, 6, 287-293.

Key Words: Brightness; contrast; distance perception

A black and a white target are displayed, in five different conditions, on five gray backgrounds having different degrees of brightness (from very bright to very dark). The results show that the target having the higher contrast with its background is perceived as the nearer. With the off-white background, for example, the black target appears as the nearer to the observer. This contradicts the well-known concept according to which the brighter target should in any case be perceived as the nearer ("relative brightness" cue). The conclusion is that the frame of reference must be taken into consideration: stating that an experiment was conducted in empty space or with relative brightness is not sufficient.

CIG Implications: Distortions in distance perception result because the angular subtense of an object cannot be reduced below the size of one pixel. These distortions may be ameliorated by reducing the contrast of an object after the one-pixel limit has been reached. The results show that this strategy will indeed produce the perception of an object receding into the distance.

Ganz, L. Temporal factors in visual perception. In Ed C. Carterette
and Morton P. Friedman (eds.), Handbook of perception, V, 169-231,
New York: Academic Press, 1975.

Key Words: Time integration; Block's Law; temporal threshold

This tutorial review is concerned with the time-integrative functions of the visual system. Light quanta are integrated by the system in time bins of 17 to 100 msec or longer. The effects of these parameters on contrast detection thresholds, flicker thresholds, and perceived duration are described.

A variety of temporal perceptual phenomena can be described by Block's law which states that for threshold phenomena, the same visual effect will be obtained if the product of the intensity and duration is held constant, so long as the duration time is less than the critical duration (estimated as 100 msec).

Recent research indicates that the effect of target size on critical duration is negligible but that the effect of background is large. Another variable affecting critical duration is the nature of the task when integration time increases to as high as 400 msec during movement of the test target and for judgments involving Landolt-C test targets. Patterns of results suggest that when higher stages of the perceptual system are involved, longer critical durations result.

It is suggested that the temporal properties that comprise Block's law are determined within the receptors themselves and possibly involve the diffusion of ions as a mechanism. Changes in time constant with background luminance can also be attributed to receptor mechanisms.

If a double light pulse varying in stimulus onset-to-onset is presented rather than single light pulses, the results are more complex. The main complication appears to be that, in response to a very brief light pulse, the visual system goes through a benevolent sequence of excitation followed by inhibition which will attenuate the impact of the second impulse if the interval is between 40 to 70 msec.

If it is assumed that the visual system is linear, one can predict the response of the system to any temporal transient if one knows the system's response to the sine wave components into which the transient can be decomposed by Fourier analysis. This transfer characteristic is the "temporal modulation transfer function" (TMTF). It is determined by presenting O's with sinusoidally flickering light and measuring, for each frequency of flicker, the amplitude needed to obtain a standard amplitude response. A number of articles are reviewed with the following conclusions presented. At average retinal illuminance of 4.3 td, the visual system responds as a simple low pass filter with a corner frequency of 7 Hz. Above 10 Hz the threshold of a flickering target of any waveform is entirely predictable from the threshold to the fundamental frequency of the sinusoid of that waveform, with higher harmonies not affecting the threshold.

With higher average luminance levels (43, then 403 td), relative sensitivity to higher frequencies improves and a peak of sensitivity develops at 8 to 10 Hz, implying that at higher photopic adaptation levels, the visual system begins to resemble a filter with both high and low frequency cutoff properties. The system operates such that humans are less sensitive to slow flicker when the field is large. The reader is referred to several sources for theoretical treatment of flicker.

A number of inferred impulse responses of the visual system to a brief transient pulse are shown for four levels of background luminance These unit-impulse responses are the Fourier transform of the TMTF. They indicate that for the highest background level the visual system responds even to a brief pulse with a latency of approximately 20 msec, with a positive-negative sequence occupying an additional 60 msec. The impulse response becomes slower as background luminance diminishes. The relationship between Block's law and temporal modulation is described.

The studies of critical duration and unit-impulse response are related to visual persistence, perception of succession, and visual numerosity.

Empirical studies of homogeneous light masking are presented. The effects are attributed to temporal integration in the visual system Similarly, empirical studies of metacontrast are reviewed with the conclusion that metacontrast involves lateral inhibition particularly among contour-sensitive mechanisms.

Several theories are presented in association with metacontrast: 1) the overtake hypothesis, 2) lateral inhibition, and 3) fast inhibition, slow excitation.

Lastly, the effects of visual-noise masking and several theoretical interpretations of the phenomenon are explicated. Among those theories discussed are: 1) processing interruption, 2) integration theory, and 3) encoding time hypothesis.

Spatiotemporal interactions involving forms of Block's law for moving objects are described. Predictions regarding apparent motion are derived.

CIG Implications: Reviews a large portion of the data which must be considered when implementing contrast management, such as temporal threshold phenomena, effects of luminance on flicker, effects of critical duration on unit-impulse responses, and spatiotemporal interactions for moving objects.

Higgins, K. E., and E. J. Rinalducci. The spatial Broca-Sulzer and sensitization effects for foveal viewing. Vision Research, 1975, 15, 423-425.

Key Words: Threshold sensitivity; contrast detection

Under certain conditions a small, circular stimulus field will appear brighter (the spatial Broca-Sulzer effect) and produce a higher increment threshold (Westheimer's sensitization effect) than a larger stimulus field of the same retinal illuminance. In this experiment, a two-stage procedure was used to compare the two effects for foveal viewing by determining if the different stimulus area-retinal illuminance combinations that are perceived as equally bright produce equivalent states of increment-threshold sensitivity. The results indicate that, while both effects are observed at comparable levels of retinal illuminance, the two effects cannot be considered synonymous.

CIG Implications: Describes the conditions where contrast detection thresholds and apparent brightness do not adhere to the typical contrast sensitivity functions of the visual system. These special circumstances must be considered for implementing effective contrast management. Otherwise the abrupt and unnatural appearance of some objects will persist.

Hirst, A. N., R. L. Beurle, K. I. Beverley, and C. L. Poole. Contrast thresholds for patterns of dynamic visual noise. Vision Research, 1979, 19, 721-725.

Key Words: Contrast thresholds; visual noise

It has previously been suggested that when using a cascade image intensifier there is an optimum gain above which contrast detection thresholds increase. This paper shows that this is only true for very low scintillation densities. At higher densities detection thresholds remain constant above the optimum gain which occurs when about 100 photons enter the pupil from each scintillation. The very low scintillation density regime appears to be a special case.

CIG Implications: Noise from quantal fluctuations need not be considered for effective contrast management except at very low light levels which are typically outside the normal operating range of simulator displays. However, scintillations derived from noise in the system itself may make this issue relevant to the quality of some display systems.

Kelly, P. H. Adaptation effects on spatio-temporal sine-wave thresholds. Vision Research, 1972, 12, 89-101.

Key Words: Adaptation; spatial frequency sensitivity; flicker

The photopic amplitude threshold (ΔB) for a stimulus that is a sinusoidal function of space and time shows both linear and nonlinear behavior as the background level (B) is changed. Flicker adaptation is linear at high temporal frequencies (ΔB = constant), but obeys a Weber type of nonlinearity ($\Delta B = kB$) at low temporal frequencies. Contrast adaptation is nonlinear at all spatial frequencies, changing from Weber's law at low spatial frequencies to a DeVries-Rose type of nonlinearity ($\Delta B = kB^{1/2}$) at high spatial frequencies. In this paper, these regions of linear and nonlinear adaptation are mapped in a general way by varying both spatial and temporal frequencies as well as the background level. The resulting spatio-temporal adaptation maps are interpreted in terms of retinal mechanisms.

CIG Implications: Contains a complete representation of the contrast sensitivity surface as a function of temporal and spatial frequency as well as background illuminance. These are the data required to implement contrast management algorithms tailored to the modulation transfer function of the human visual system. These data are most relevant when the contrast of periodic patterns is at issue.

Kelly, P. H. Theory of flicker and transient responses, I. Uniform fields. Journal of the Optical Society of America, 1971, 61, 537-544.

Key Words: Modulation transfer; flicker

Photopic flicker data are explained in terms of a theoretical model of two retinal processes. The first is a linear diffusion process (presumably in the receptors) with a large dynamic range ($\sim 10^5$). The second is a nonlinear inhibiting network (neural feedback at the synapses of the plexiform layers) that adaptively controls the sensitivity and time constants of the model. The magnitude of its transfer function fits the flicker data quantitatively at all frequencies, over a wide range of adaptation levels. The corresponding small-signal impulse responses are also calculated: their latencies and leading edges (associated with receptor activity) are invariant with adaptation level, and the remaining phases of these transient waveforms (associated with the graded potentials of secondary neurons) adapt strongly, in accord with current histology and microelectrode findings.

CIG Implications: Presents basic data on the perception of flicker. The article is useful for determining the required update rates to eliminate flicker and when aliasing problems will result in an undesirable flicker response. Furthermore, the simple theory presented may aid in the development of algorithms to deal with these issues.

Kitterle, F. L., and T. R. Corwin. Enhancement of apparent contrast in flashed sinusoidal gratings. Vision Research, 1979, 19, 33-39.

Key Words: Apparent contrast; exposure duration

The apparent contrast of suprathreshold grating targets was measured as a function of their spatial frequency and exposure duration. For targets of low spatial frequency, apparent contrast reaches a maximum at exposure durations of 80 to 100 msec relative to its value at shorter and longer durations. Contrast-duration curves thus resemble brightness-duration curves when the Broca-Sulzer effect is present. For gratings of higher spatial frequency, apparent contrast increases monotonically with duration. Thus, temporal contrast enhancement occurs only for low spatial frequency targets. The enhancement effect occurs foveally as well as for peripherally viewed targets, but it is abolished by decreasing the vertical extent of the grating.

CIG Implications: The temporal parameters required for effective contrast management apply to the apparent contrast of suprathreshold stimuli as well as to visual forms at threshold contrast levels. Thus, in order to maintain real-world values of relative contrast within the display's limited dynamic range, an object's presentation duration must be considered for low spatial frequencies.

Koenderink, J. J., M. A. Bowman, A. E. Bueno de Merquita, and S. Slappendal. Perimetry of contrast detection thresholds of moving spatial sine wave patterns, I. The near peripheral visual field. Journal of the Optical Society of America, 1978, 68, 845-849.

Key Words: Peripheral vision; contrast detection

Contrast detection thresholds for moving spatial sine wave gratings were obtained for two subjects at the fovea and at eccentricities of 1°, 2°, 4°, 6°, and 8° on the nasal horizontal meridian. The target field subtended 30 x 30 min of arc. The spatial frequency range extended from 2 cpd up to the spatial resolution limit; the temporal frequency range from 0.1 Hz up to the CFF. Mean retinal illuminance was 10 trolands. For these conditions: 1) contrast detection thresholds are higher, the higher the spatial and/or temporal frequency of the stimulus; 2) acuity appears to be independent of the temporal frequency and the CFF appears to be independent of the spatial frequency; and 3) the higher the eccentricity, the higher the contrast detection threshold for any drifting sine wave pattern. The threshold doubles roughly any 2° to 3° for spatial frequencies of 2 to 20 cpd, except that the visual field for a given fineness of grating is blind beyond a certain critical eccentricity. This critical eccentricity is a monotonically decreasing function of the spatial frequency of the grating. These measurements do not support the hypothesis that coarse patterns are preferentially detected at extrafoveal sites in the visual field.

CIG Implications: The data indicated that peripheral contrast thresholds may be ignored for setting contrast levels in the data base since foveal vision is more sensitive. However, if it were known where on the display a pilot was looking, the level of detail displayed in peripheral fields could be substantially reduced.

Koenderink, J. J., M. A. Bowman, A. E. Bueno de Merquita, and S. Slappendal. Perimetry of contrast detection thresholds of moving spatial sine wave patterns, II. The far peripheral visual field. Journal of the Optical Society of America, 1978, 68, 850-853.

Key Words: Peripheral vision; contrast detection

Contrast detection thresholds for moving sine wave gratings were obtained at the fovea and at eccentricities of 6°, 12°, 21°, 32°, and 50° on the nasal horizontal meridian. The field subtended 4° x 4°. Spatial frequencies ranged from 0.25 cpd up to the resolution limit; temporal frequencies from 0.1 Hz up to the CFF. Mean retinal illuminance was 10 trolands. For these conditions: 1) for any eccentricity there exists a unique combination of spatial frequency and velocity for which the threshold is a minimum (extremes are 2 cpd and 2° s^{-1} at the fovea, and 0.5 cpd and 12° s^{-1} at an eccentricity of 50°); 2) acuity depends little on velocity, and the CFF only little on spatial frequency; and 3) the higher the eccentricity, the higher the threshold for any drifting sine wave pattern. Except for these cases, the qualitative threshold behavior as a function of spatial and temporal frequency is identical at the fovea and at eccentricities up to 50°. The thresholds double every 12° for spatial frequencies of 0.25 to 2 cpd. For a given spatial frequency the visual field is blind beyond a certain critical eccentricity. This critical eccentricity is a monotonically decreasing function of spatial frequency.

CIG Implications: The superior sensitivity of foveal vision allows one to ignore peripheral thresholds for determining contrast levels for objects and levels of detail in the data base. However, the result is that much more detail is displayed in the peripheral visual fields than can be perceived.

Koenderink, J. J., M. A. Bowman, A. E. Bueno de Merquita, and S. Slappendal. Perimetry of contrast detection thresholds of moving spatial sine wave patterns, III. The target extent as a sensitivity controlling parameter. Journal of the Optical Society of America, 1978, 68, 854-859.

Key Words: Peripheral vision; contrast detection

Contrast detection thresholds for moving sine wave gratings were obtained at the fovea and at eccentricities of 6°, 21°, and 50° on the nasal horizontal meridian. The targets subtended from 30 x 30 min of arc up to 16° x 16°. It was found that the contrast detection thresholds depend critically on the extent of the target field. If this extent is large enough, peripheral detection thresholds are on a par with those measured at the fovea, but the sensitivity range is shifted to lower spatial frequencies. If the just-resolvable distance at any eccentricity is taken as a yardstick, and field width and spatial frequency are scaled accordingly, then the spatiotemporal contrast detection thresholds become identical over the whole visual field. It is shown that a smallest area, measuring several just-resolvable distances across, has to be stimulated before successive or simultaneous contrast detection is possible at all. Detection performance improves if the stimulated area is enlarged up to diameters of at least 10^2 just-resolvable distances. The just-resolvable distance correlates well with mean interganglion cell distance and with the cortical magnification factor.

CIG Implications: Provides data relevant to more effective contrast management in the peripheral visual field.

Kulikowski, J. J. Some temporal parameters affecting spatial and temporal resolution of human vision. Vision Research, 1971, 11, 83-93.

Key Word: Contrast

Contrast threshold was measured psychophysically for a sinusoidal grating presented periodically with a variable temporal frequency for various parameters of patterns. Special attention was paid to the range of high spatial frequencies as defining the resolving power of the eye. Within this range, the contrast threshold were found to be almost independent of many parameters of patterns. It was also found that the sum of certain spatial and temporal resolution indices was proportional to the logarithm of the contrast; this sum was also a logarithmic function of the average luminance in the mesoptic range of luminances.

CIG Implications: For high spatial frequencies, temporal parameters may be treated as independent of spatial parameters for the development of contrast management algorithms.

Lamar, E. S., S. Hecht, S. Shlaer, and D. Hendley. Size, shape, and contrast in detection of targets by daylight vision, I. Data and analytical description. Journal of the Optical Society of America, 1947, 37, 531-545.

Key Words: Contrast; target size and shape

The influence of size and symmetry has been studied on the contrast required for the recognition of rectangular targets against background brightnesses of 2950 and 17.5 foot-lamberts. Targets less than 2 minutes in diameter require the addition of a constant total light flux to the background. Larger targets require less contrast but more total flux as the area increases, until beyond 200 square minutes when the required contrast becomes independent of area. For areas below 100 square minutes, square targets are most efficient for their area; the greater the ratio of length to width, the greater the contrast required. All the measurements can be unified on the supposition that the visually critical region of a target is a ribbon just inside its perimeter and about 1 minute wide. Evidently, contrast is not judged over the area of a target, but across its boundary.

CIG Implications: Provides a great deal of basic data relevant to the implementation of more effective contrast management, as discussed in Subsection 2.1.

Legge, G. E. Space domain properties of a spatial frequency channel in human vision. Vision Research, 1978, 18, 959-969.

Key Words: Spatial frequency; sine wave gratings; contrast sensitivity function; spatial summation; probability summation

Many properties of contrast detection in human vision may be described with reference to a set of tuned spatial frequency channels. The spatial sensitivity of the channel with optimal sensitivity at 3.0 c/deg was studied by measuring theshold as a function of the width of truncated 3.0 c/deg sine wave gratings that ranged from 2.3' to 4.6°. Three strategies were used to isolate the threshold response of the channel: 1) the channel at 3.0 c/deg was chosen because of its position at the peak of the contrast sensitivity function; 2) a discrimination paradigm was used in which test stimuli were superimposed on a low contrast grating which was shown to selectively facilitate their detection; 3) the detecting channel was more sensitive to the sine wave configuration of the test stimuli than to more conventional spatial summation stimuli, such as rectangular bars. Results of the main experiment showed that threshold contrasts for the truncated sine wave stimuli declined in two stages. From 2.3' to 40', the threshold decline was steep, with a plateau at 10'. From 40' to 4.6°, threshold declined as a power function of stimulus width with an exponent of -0.35. The data of the main experiment were used to derive the spatial receptive field sensitivity for the channel at 3.0 c/deg. The data were accounted for by spatial summation within a receptive field and probability summation in space across receptive fields.

CIG Implications:

1) Provides detailed information relevant to contrast management in the spatial frequency range where the visual system is most sensitive.

2) The interaction of other simultaneously present spatial frequencies with a 3.0 c/deg target is relevant to raster effects which are typically between 6 and 8 c/deg.

Legge, G. E. Sustained and transient mechanisms in human vision: temporal and spatial properties. Vision Research, 1978, 18, 69-81.

Key Words: Modulation transfer; spatial frequency

In two experiments, properties of sustained and transient mechanisms were studied psychophysically. In the first, contrast thresholds were measured for 6 sine wave gratings ranging from 0.375 to 12.0 c/deg at 10 durations ranging from 18 to 3000 msec. Thresholds were measured in the presence and absence of high contrast 20 msec gratings which masked the onsets and offsets of the signals. At 1.5 c/deg and above, the unmasked thresholds decreased as power functions of duration in two stages, reaching an asymptotic level near 1000 msec. Below 1.5 c/deg, the unmasked threshold became independent of duration beyond 100 msec. At all frequencies, the masked thresholds decreased as power functions of duration to 1000 msec or more, but the curves for 0.375 and 0.75 c/deg never reached the unmasked asymptotic level. In the second experiment, spatial frequency bandwidths were obtained for sine wave gratings ranging from 0.375 to 12.0 c/deg by measuring threshold elevation as a function of the spatial frequency of masking gratings. At 3.0, 6.0 and 12.0 c/deg, the bandwidth functions peaked at the signal frequencies and showed medium bandwidth frequency selectivity. Below 1.5 c/deg, the bandwidth functions exhibited broader spatial frequency tuning and were of higher magnitude, and there was a shift in peak masking to frequencies near 1.0 to 1.5 c/deg which were above the signal frequencies. The results of both experiments are discussed in terms of the sustained/transient dichotomy.

CIG Implications:

1) The detection of higher spatial frequencies increases with stimulus duration up to about 1 sec. Therefore, if an object or level of detail is switched in at or near threshold levels, its perception will increase in a natural manner after it is displayed.

2) The increased sensitivity to low spatial frequencies will cause large objects to pop in and out of view as they approach the edges of the display field. Methods for mitigating these effects are discussed in Subsection 2.1.

Marks, L. E. Brightness and retinal locus: effects of target size and spectral composition. *Perception and Psychophysics*, 1971, 9, 26-31.

Key Words: Brightness; foveal and peripheral sensitivity

Subjects gave numerical estimates of brightness for stimuli presented to the foveal and peripheral retina. Experiment 1 showed that the periphery's superior sensitivity to white light is relatively independent of target size. Experiment 2 showed that the periphery is more sensitive than the fovea to violet light, but is less sensitive than the fovea to red light. These results are explicable in terms of differences between rod and cone mediation of brightness.

CIG Implications: The development of effective contrast management algorithms can be based entirely on the sensitivity of foveal vision. Peripheral sensitivity in terms of brightness and color is less than foveal sensitivity with only a few exceptions that have no practical significance in current display systems.

Osaka, N. Perceived brightness as a function of flash duration in the peripheral visual field. Perception and Psychophysics, 1977, 22, 63-69.

Key Words: Peripheral vision; perceived brightness

Using a method of direct magnitude estimation, perceived brightness was measured in the dark-adapted eye with brief flashes of varying duration (1 to 1,000 msec), size (16' to 116'), and retinal loci (0° to 60°) for the lower photopic luminance levels covering the range between 8.60 and 0.86 cd/m^2 in steps of 0.5 log units. Perceived brightness increased as a function of flash duration as well as luminance up to approximately 100 msec, then remained constant above 100 msec. The enhancement of brightness at about a 50-msec flash duration has been observed not in the fovea but in the periphery. Target size also has been found to effect brightness.

CIG Implications: The increased sensitivity of peripheral vision to transient stimuli suggests that the unnatural and abrupt appearance of objects discussed in Subsection 2.1 may be enhanced when viewed peripherally. This effect can result in inappropriate eye movements toward objects that suddenly pop into view in peripheral vision.

Rose, D. Monocular versus binocular contrast thresholds for movement and pattern. Perception, 1978, 7, 195-200.

Key Words: Monocular and binocular vision; apparent movement

The superiority of binocular vision over monocular vision was compared both for the detection of stationary sinusoidal grating patterns and for the detection of the apparent movement induced by rapidly phase-reversing such gratings. The thresholds for binocular and monocular pattern perception were in the ratio $1:2^{1/2}$, as found by previous workers. For apparent movement, however, binocular thresholds were lower than monocular thresholds by a factor of 1:9; for every subject tested (n=20) the ratio for movement detection was larger than the ratio for pattern detection. The effects of combining inputs from the two eyes cannot be explained solely by linear summation models, but may in some circumstances depend on the nonlinearities of certain types of nerve cells.

CIG Implications: Since much of the psychophysical threshold data available used monocular viewing conditions, these thresholds should be modified to reflect the binocular viewing of the simulator display.

Schade, O. H. Optical and photoelectric analog of the eye.
Journal of the Optical Society of America, 1956, 9, 721-739.
Key Word: Physical eye model

A photoelectric analog of the visual system is constructed in conformance with anatomical data. The analog has the form of a color television camera chain-feeding electrical signals to a "computer" (the brain). Evaluation of characteristics is limited to elements preceding the computer, and particularly to the "luminance channel" of the color system.

The primary photoelectric transfer characteristics $n_1=f(E_r)$ of the receptors (rods and cones) are computed as a function of retinal illumination (E_r) from threshold signal-to-noise ratios in the effective image area of point sources, disks, and other test objects. The effective image area, which is the convolution of the object area with the sampling area of the visual system, is determined from its Fourier spectrum. The constants of the transfer functions are established from the optical constants of the eye, its storage-time function, and the maximum transfer ratio of statistical units of the rod and cone systems. There is a little room for variation of constants, if they are to remain in agreement with observed values.

The incomplete DC restoration in the system (differentiation of edges) is taken into account as a negative image component caused by feedback. System design principles are used as a guide in calculating the signal integration by retinal elements and the relative photoconductor gain characteristics of the receptors which are part of a system of interdependent functions including the primary characteristic, the overall transfer characteristic to the optic nerve lines, and the four spatial integration characteristics represented by the equivalent passbands of lens and retina for the rod and cone systems.

The final solution is perhaps not completely unique for all functions, but does not violate or disagree with fundamental principles or observations as demonstrated by a comparison of the operating characteristic of the analog with the Munsell lightness scale, its noise level with perception of external noise, and its statistical transfer ratio, relative gain, gamma, and feedback with observed data. The acuity, contrast sensitivity, and threshold visibility of point sources of the analog are, of course, in inherent agreement with corresponding properties of the eye.

CIG Implications: This article is the first attempt at using Fourier analysis to describe the human visual system. The optical and photoelectric analog presented in this paper may prove useful in the development of algorithms for effective contrast management.

Shlaer, S. One relation between visual acuity and illumination.
Journal of General Physiology, 1937, 21, 165-188.

Key Words: Acuity; illumination; historical development

An apparatus for measuring the visual acuity of the eye at different illuminations is described. The relation of visual acuity and illumination for trained observers was measured using a broken circle and a grating. Both test objects show a break at a visual acuity of 0.16; values above 0.16 are mediated by cones and values below are mediated by rods. The grating gives higher visual acuities at intensities less than 30 photons and lower visual acuities above that. With conditions equal, the maximum visual acuity obtainable with the grating is approximately 30% lower than that with the circle. When pupil diameter is less than 2.3 mm, it is the limiting factor in resolution of the eye for the grating; when larger than 2.3 mm, the size of the central cones is the limiting factor. The data derived from the cones with both test objects are adequately described by previously derived equations for the photoreceptor system. The authors conclude that detail perception is a function of a distance rather than an area.

CIG Implications: Although some of the explanatory mechanisms presented here have undergone changes since the publication of this article, the data are still quite relevant to contrast management viewed as a line spread function.

Stromeyer, C. F., A. F. Lange, and L. Ganz. Spatial frequency phase effects in human vision. Vision Research, 1973, 13, 2345-2360.

Key Word: Spatial frequency phase effects

Color aftereffects (McCoullough effects) were generated specific to each member of a pair of vertical gratings which had identical frequency spectra but which differed in the phase angles between their frequency components. The pairs were either left- and right-facing sawtooth gratings or gratings comprising the sum of two harmonies--first and second, first and third, or first and fourth. Color aftereffects were readily obtained with sawtooth gratings (which had sharp edges) and with patterns comprising first and second harmonics; the effects were very weak with the first and third harmonic patterns and almost absent with the first and fourth harmonic patterns. The results suggest that there are phase-sensitive broadband mechanisms within the visual system and that each "spatial frequency channel" cannot be simply represented by a single, symmetric line spread function.

CIG Implications: Relevant to the masking effects produced by a visible raster and the limitations of using only the line spread function for the development of contrast management algorithms.

Thomas, J. P. Spatial summation in the fovea: asymmetrical effects of longer and shorter dimensions. Vision Research, 1978, 18, 1023-1029.

Key Word: Spatial summation

Spatial summation was measured for foveally viewed rectangles superimposed on a 1000-td background. The longer and shorter dimensions of the stimuli were independently varied from 0 to 50'. Visibility increased as the longer dimension was increased up to 40 or 50'. However, changes in the shorter dimension affected visibility systematically only when the shorter dimension was less than 5'. When the stimulus was near the luminance threshold, the shorter dimension was more accurately estimated than the longer dimension. The results suggest that the detection is mediated by only those spatial frequency components which lie parallel to the long axis of the stimulus.

CIG Implications: Provides data required for the implementation of more effective contrast management. Given that a pixel typically subtends approximately 4 to 6 minutes of visual angle, controlling the appearance of objects as viewing distance decreases will require setting the contrast threshold in terms of the object's longer dimension.

Van Nes, F. L., J. J. Koenderink and M. A. Bowman, Spatiotemporal modulation transfer in the human eye. *Journal of the Optical Society of America*, 1967, 57, 1082-1088.

Key Words: Modulation transfer; contrast sensitivity; flicker

The contrast sensitivity of the human eye for sinusoidal illuminance changes in space and time, obtained by means of traveling-wave stimuli, was measured as a function of spatial and temporal frequency for white light. The average retinal illuminance was varied between 0.85 and 850 trolands. The threshold modulation for perception of a moving grating is generally higher than that for detection of brightness changes, in space and/or time, that give rise to flicker phenomena. Flicker-fusion characteristics, as determined from the thresholds for the flicker phenomenon, are found to lose their band-pass-filter resemblance for spatial frequencies of more than 5 cycles per degree of visual angle. The thresholds at flicker fusion for spatial- and temporal-frequency combinations in which at least one frequency is not very low appear to be proportional to the inverse of the square root of mean retinal illuminance (in the investigated range). This suggests a photon-noise-dependent threshold mechanism which is operative in a wider illuminance range than that found with contrast-sensitivity measurements for periodic illuminance variations only in space or only in time.

CIG Implications: Effective contrast management requires a knowledge of the effect that spatial and temporal stimulus parameters have on detection thresholds. The temporal parameters are especially important for dynamic CIG displays. This article contains a portion of the available data on the detection of flicker at various spatial frequencies and the human's contrast sensitivity to these spatial frequencies as a function of the signal's temporal modulation.

Wilson, H. R., and J. R. Bergen, A four mechanism model for threshold spatial vision. Vision Research, 1979, 19, 19-32.

Key Words: Line spread function; threshold spatial function

Data on the threshold visibility of spatially localized, aperiodic patterns are used to derive the properties of a general model for threshold spatial vision. The model consists of four different size-tuned mechanisms centered at each eccentricity, each with a center-surround sensitivity profile described by the difference of two Gaussian functions. The two smaller mechanisms show relatively sustained temporal characteristics, while the larger two exhibit transient properties. All four mechanisms increase linearly in size with eccentricity. Mechanism responses are combined through spatial probability summation to predict visual thresholds. The model quantitatively predicts the spatial modulation transfer function (cosine grating thresholds) under both sustained and transient conditions with no free parameters.

CIG IMplications:

1) Contains basic threshold data for single objects as a function of size and temporal waveform. Thresholds for single objects cannot be accurately estimated from studies using sine wave gratings or other complex periodic patterns.

2) Hypothesis that there is a limited number of size detectors in the visual system might prove useful in future construction of CIG data bases in the same manner that the visual system's three color-detecting mechanisms have been exploited for the representation of color.

B.2 RESOLUTION

All the displays examined were limited in resolution relative to the acuity of foveal vision. This limitation restricts the range of perceptual tasks that can be realistically simulated in current display systems. The research summarized in this subsection documents those perceptual abilities that exceed the capabilities of current simulators.

Baker, E. E. Some variables influencing vernier acuity. Journal of the Optical Society of America, 1949, 39, 567-576.

Key Words: Vernier acuity; illumination; exposure; color

Functions relating vernier acuity to illumination were obtained for two different exposure times and at 3 regions of the visual spectrum. Vernier acuity is low at low levels of brightness, rises with an increase in illumination, and levels off at high brightness levels. Vernier acuity is displaced downward for short exposures; the maximum vernier acuity is best reached by higher illuminations than by long exposures. Variations in the functions with exposure durations of the acuity object are interpreted by intensity-time relationships and previous findings on the effect of exposure time on brightness discrimination.

Investigations of the influence of color on vernier acuity show that all functions are similar, but different maximum acuities are reached with different colored illuminations. The colors give acuity in the following order, from highest to least: red, yellow, white, blue. If refractive correction is made to allow for sharp focusing with blue illumination, highest acuities are found for this color.

Color of illumination is significant for vernier acuity, since higher acuities are found with nearly monochromatic light than with white. The blurring of retinal images that is caused by restricting the range of wavelengths may cause this improvement.

CIG Implications: Under optimal viewing conditions the human observer can easily detect changes in position, size, and orientation which are very small relative to a pixel (the resolution limit of a display). However, these changes can be represented in the display by convoluting the image with a blurring function, as discussed in Subsection 2.2.

Butler, T. W., and G. Westheimer. Interference with stereoscopic acuity: spatial, temporal, and disparity tuning. Vision Research, 1978, 18, 1387-1392.

Key Word: Stereoscopic acuity

Stereoscopic acuity (the ability to detect differences in the depths of objects as small as 2") is conspicuously reduced by the presence of contours contiguous to the test pattern. Flanking contours interfere maximally when they are placed about 2.5' from a test line, and less when this distance is increased or decreased. The largest interference effect is obtained when the flanks are presented 100 msec after the onset of the test pattern. The interference has a quite narrow depth tuning: to halve the threshold elevation the flanks must be presented only 12", 17" and 40" out of fixation plane for the three subjects, respectively.

CIG Implications: Steroscopic acuity of the human visual system greatly exceeds the resolution limits of current simulator displays. Some of the displays' resolution limits can be circumvented by convoluting the image with a blurring function, as discussed in Subsection 2.2.

Campbell, F. W., and J. G. Robson. Application of Fourier analysis to the visibility of gratings. Journal of Physiology, 1968, 197, 551-566.

Key Words: Modulation transfer; grating shape

This study measured the contrast thresholds of a variety of grating patterns over a wide range of spatial frequencies. The results showed that contrast detection thresholds for gratings whose luminance profiles are sine, square, rectangular or sawtooth waves can be simply related using Fourier theory. Over a wide range of spatial frequencies the contrast threshold of a grating is determined only by the amplitude of the fundamental Fourier component of its waveform. Gratings of complex waveform cannot be distinguished from sine wave gratings until their contrast has been raised to a level at which the higher harmonic components reach their independent threshold. These findings are explained by the existence within the visual system of linearly operating independent mechanisms selectively sensitive to limited ranges of spatial frequencies.

CIG Implications:

1) For the detection of complex periodic patterns, only the fundamental Fourier component need be displayed when contrast is near threshold levels.

2) Discrimination among different complex patterns requires the display of their higher harmonics which may exceed the resolving power of the display system.

Kulikowski, J. J. Effect of eye movements on the contrast sensitivity of spatio-temporal patterns. Vision Research, 1971, 261-273.

Key Word: Contrast sensitivity

The contrast sensitivity (the reciprocal of the contrast threshold) was measured under various conditions of fixation such as normal involuntary eye movements, tension tremor, post-rotation nystagmus, and the coarse stabilization of the retinal image. Most of the exaggerated eye movements reduced the contrast sensitivity for patterns of either low spatial or low temporal frequencies, and increased the sensitivity at high spatial and high temporal frequencies. Possible roles of the eye motion in detection of the spatiotemporal patterns are discussed.

CIG Implications: For most practical purposes, large eye movements decrease acuity and effectively narrow the gap between the resolution of the eye and the simulator display. The display's limited resolution is most problematic when the observer is able to fixate on stationary or slowly moving objects.

Sloan, L. L. The photopic acuity-luminance function with special reference to parafoveal vision. Vision Research, 1968, 8, 901-911.
Key Word: Parafoveal vision

The linear relation between decimal acuity and log luminance, well established for the fovea, is also found for parafoveal areas of the retina. The parafoveal acuity-luminance function has a slower rate of change of acuity with log luminance and reaches maximal acuity at a lower luminance. Changes in retinal organization and their effects on the density of functional receptor units probably contribute to the observed regional differences.

CIG Implications: Since parafoveal acuity is less than foveal acuity, only foveal acuity need be considered for simulator displays. Furthermore, given the limited resolution of most displays, scene elements falling in peripheral vision will appear more realistic than those elements on which the user fixates.

Thomas, J. P. Spatial resolution and spatial interaction. In Ed. C. Carterette and Morton P. Friedman (eds.), Handbook of Perception, V, New York: Academic Press, 1975.

Key Words: Spatial visual perception; pattern resolution; special interaction

This article discusses two aspects of spatial visual perception: resolution of spatial patterns and phenomena of spatial interaction. The topics are treated separately and then integrated with respect to theoretical interpretation.

Spatial resolution is discussed in terms of measurement (acuity and contrast sensitivity) and as a function of several stimulus variables affecting performance, e.g., intensity of illumination, retinal locus, pupil size, spectral composition of illumination, orientation and viewing distance. Theoretical issues involving 1) effect of the intensity of field illumination, 2) optical or neural limitations, and 3) spatial frequency tuning are discussed.

Spatial interaction is similarly treated with discussion of types of interactions that occur and measurement of the effects of a number of variables (e.g., size of test stimulus, background illumination, and sharpness of stimulus contours).

Three mechanisms are described which must be considered when interpreting the phenomena of spatial interaction: stray light, eye movements and neural interaction.

CIG Implications: Provides an overview of those variables affecting the detection and identification of visual patterns that must be considered to control the appearance of objects as a function of this calculated view distance, i.e., contrast management and resolution.

Van Doom, A. J., J. J. Koenderink, and M. A. Bowman. The influence of the retinal inhomogeneity on the perception of spatial patterns. Kybernetics, 1972, 10, 223-233.

Key Words: Retina inhomogeneity; retinal model; foveal vision

From the fact that the retina is rather inhomogeneous, it can be inferred that the perception of spatial patterns of appreciable extent will be dependent on the retinal location. Anatomical, electrophysiological and psychophysical findings substantiate the claim that the composition of the retina is very inhomogeneous. To investigate the influence of this inhomogeneity on the perception of patterns, a model of spatiotemporal signal processing in the retina was developed on the basis of a paradigm for the Weber-type adaptation. Such "scaling-ensembles" proved successful in the prediction of spatiotemporal modulation transfer in the human fovea. One prediction of the present model is that certain spatial patterns are optimally detected at well defined retinal locations. A confrontation of the model's predictions with measurements published by Bryngdahl (1966)* made it possible to estimate some of the relevant parameters of the retinal receptive fields as a function of the eccentricity. Obtained estimates compare reasonably well with previously known values; for instance, with values of acuity and anatomical measurements. The discussion is relevant to the question of whether the retina is composed of independently tuned spatial frequency filters at any retinal location, or whether the tuning is with respect to the eccentricity.

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*Bryngdahl, O. Perceived contrast variation with eccentricity of spatial sine-wave stimuli: size determination of receptive field centers. Vision Research, 1966, 6, 553-565.

CIG Implications: Peripheral visual acuity appears to follow the same psychophysical laws found in foveal acuity once the differences in the distribution of rods and cones are taken into account. Therefore, the resolution of current CIG systems is adequate for peripheral vision acuity and does not require special algorithms to effect appropriate contrast management.

Westheimer, G. Spatial phase sensitivity for sinusoidal grating targets. Vision Research, 1978, 18, 1073-1074.

Key Words: Modulation transfer; phase

Because the full specification of a sinusoidal grating target must include phase as well as amplitude, an experiment was performed to determine the phase sensitivity for sinusoidal gratings in central vision for normal human observers. Phase displacement thresholds for sinusoidal gratings ranging in spatial frequency from 3 to 25 cycles/degree are a linear function of spatial frequency (1° of phase angle per c/deg). The just-detectable lateral distances are constant and equal to those for a single line.

CIG Implications: The ability of the visual system to detect changes or differences in position (i.e., phase) far exceeds the resolution limits of CIG displays when represented by a single line. However, the findings of this study indicate that these small displacements can be represented in the display by a gradient of illumination which extends over several pixels. (See Subsection 2.2.)

Westheimer, G., and G. Hauske. Temporal and spatial interference with vernier acuity. Vision Research, 1975, 15, 1137-1141.

Key Word: Vernier acuity

Vernier resolution is substantially reduced when onset asynchrony of the two lines of the target reduces the simultaneous exposure of both lines to 100 msec or less. It is shown that this reduction is caused by backward interference of the target component that remains exposed. Temporal interference of short-exposure vernier resolution is limited to the 150 msec following the target presentation and to a spatial region of about 10 ft flanking the stimuli. The most effective interference is caused when line-interfering stimuli are at a distance of 3 to 6 ft, not when they are superimposed on the vernier target. The orientation of the interfering lines is not critical. Quantitative analysis of the results eliminates ocular light scatter as the principal origin of the phenomena, and the fact that interference with vernier acuity still occurs with dichoptous testing rules out the retina as the site of interaction.

CIG Implications: Vernier acuity (the ability to detect very small misalignments of two line segments) is well beyond the resolution limits or pixel size of current simulator displays. However, as explained in Subsection 2.2, these small differences in position can be represented in the display by convoluting the edges of the line segments with a blur function. The present study indicates that this procedure may be necessary only when the line segments have the same temporal onsets or phase.

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Westheimer, G., and S. P. McKee. Visual acuity in the presence of retinal-image motion. Journal of the Optical Society of America, 1975, 65, 847-853.

Key Word: Resolution thresholds

Resolution thresholds for Landolt C and vernier targets remain the same whether the target is stationary or moving with horizontal or vertical velocities of up to 2.5°/sec for foveal presentation lasting 0.1 and 0.2 sec. Oblique target motions are tolerated only up to 1°/sec. Because visual pursuit is ruled out by randomization of direction of motion and by the short exposure, it is concluded that a stationary retinal image is not a prerequisite for good acuity.

CIG Implications: 1) Convolution of vernier targets with a blur function is required to represent these small spatial displacements even when the targets are in motion, and 2) the breakup of edges and contours due to aliasing is especially noticeable when they are in motion. The negligible decrease in vernier acuity with motion may account, in part, for this effect. Furthermore, the convolution of moving contours with a blur function may attenuate the perception of some of these aliasing problems.

B.3 DYNAMIC RANGE

The range of light intensities in the natural world is orders of magnitude greater than that of any existing or foreseeable CIG system. The limited dynamic range of the CIG system manifests itself in several ways. For example, point sources of light cannot be represented with enough intensity to have the same visibility or apparent brightness that the sources have in the real world. (For other examples, see Subsection 2.3.) However, since the visual system is more sensitive to relative brightness or contrast than to the absolute intensity of illumination, some simple steps can be taken to mitigate the problems posed by limited dynamic range. The basic strategy is to accurately represent the relative brightness of objects in the real world within the display's limited dynamic range. Articles describing the basic characteristics of the visual system that are required to implement this strategy are summarized on the following pages.

Bryngdahl, O. Perceived contrast variation with eccentricity of spatial sine-wave stimuli: size determination of receptive field centers. Vision Research, 1966, 6, 553-565.

Key Words: Subjective contrast; receptive fields

The perceived brightnesses of the maxima and minima in a sinusoidally varying luminance distribution in space has been examined by supra-threshold techniques. The stimulus variables were the eccentricity and the spatial wavelength of the sine wave pattern. The psychophysical method used and the measurements performed are described. The sine wave patterns had 50% intensity modulation and an average luminance corresponding to 63 trolands. A clear dependence of the extreme response levels upon retinal location was found; the maximum perceived contrast and the spatial wave-length for which this maximum occurs increase with increasing distance from the fovea centralis. An estimate of the size of the receptive field center is given. A sensitivity distribution within the receptive field consisting of the difference between two Gaussian distributions is assumed. The horizontal diameter of the receptive field center was found to vary from 20μ at the fovea centralis to 100μ at 10° eccentricity.

CIG Implications: Since the above changes in apparent brightness with retinal location will occur normally in actual flight conditions, they will also occur in the simulator in a natural manner if foveal brightness functions are used to model algorithms for dynamic range compression.

Diamond, A. L. Brightness of a field as a function of its area. Journal of the Optical Society of America, 1962, 52, 700-706.

Key Words: Brightness; spatial summation

The brightness of a test field as a function of its area was investigated in the fovea at different levels of luminance. A circular test field that varied in area was presented to the subject's right eye. A circular match field that was held at a constant intermediate area was presented to the subject's left eye. The subject's task was to match the two fields in brightness by using the psychophysical method of limits. The dependent variable was the test luminance required either to match a constant luminance or to produce a constant threshold effect. The test-field radius was varied in six steps from 2.69' to 26.86' for any one of six levels of match-field luminances from threshold to 2.56 log mL. The results showed that only at threshold were there systematic differences in test luminance as a function of test area. Threshold luminance decreased as area increased. At suprathreshold test luminances, differences that did occur were neither systematic nor greater than might occur from day to day. A theoretical account is presented based upon possible inhibitory interaction in the retina of "on" by "off" nerve fibers. Curves generated by this theory are fitted to the data.

CIG Implications: Relevant for determining the relative contrast or brightness among scene elements that will produce a realistic perception of contrast within the display's limited dynamic range. According to this study, the size of a light source does not affect apparent brightness. Other studies have indicated that size does have a small effect on brightness. In either case, one can ignore stimulus size for suprathreshold illumination and still obtain a good approximation of relative contrast.

Diamond, A. L. Foveal simultaneous contrast as a function of inducing-field area. Journal of Experimental Psychology, 1955, 50, 144-152.

Key Words: Contrast; foveal vision

The apparent brightness of a 33' test-field square is studied as a function of the area and luminance of an inducing-field square, the area varying from zero to double that of the test field. A binocular matching technique is used in two experiments. These differ in the method of holding constant the spatial separation between the test and inducing fields while the inducing-field area is varied. Experiment I holds constant the distance between the near borders of the two fields. Experiment II holds constant the distance between their centers. It is pointed out that neither method of spatial-separation control is justified, and that it is theoretically more correct to assume that, along with inducing-field area variation, spatial separation is also being varied.

The results for both experiments show that the test-field apparent brightness decreases as the area of the inducing field increases, but only for inducing-field luminance equal to or greater than the test-field luminance. In Experiment II, the test-field apparent brightness is relatively less affected by the smaller inducing-field areas than it is in Experiment I, although the effect is the same for the largest area.

CIG Implications: This experiment is relevant to maintaining natural levels of relative contrast among objects within a CIG display's limited dynamic range. The decreasing apparent brightness of an object with increasing size of the background field will be realistically simulated by simply setting the relative contrast of objects in the data base to match those of the real world.

Furchner, C. S., J. P. Thomas, and C. W. Campbell. Detection and discrimination of simple and complex patterns at low spatial frequencies. Vision Research, 1977, 17, 827-836.

Key Words: Low spatial frequencies; detection; discrimination

These experiments examined the extent to which low spatial frequencies are processed independently. The assessment was carried out with respect to both detection and discrimination performance. For simple sinusoidal gratings, pairs of stimuli could be discriminated when their contrasts reached threshold if the ratio of their spatial frequencies was 3:1 or larger, a result that suggests independent processing in separate channels. For smaller frequency ratios, slightly more contrast was required for discrimination than for detection, suggesting that stimuli were not processed by entirely separate channels. The detection and discrimination thresholds of complex grating stimuli fell within the ranges which would be expected if probability summation effects and summation of different closely spaced harmonic frequencies within single channels are considered. This result supports the hypothesis of independent processing of low spatial frequency information. The single exception to this support involved discrimination of a square wave from a square wave with its fundamental component removed. In this case, discrimination required considerably more contrast than detection, even when factors of probability summation and within-channel summation of harmonics were considered.

CIG Implications: The visual missing fundamental provides an example of a filtered display that cannot be perceptually discriminated from an unfiltered display. Thus, these results demonstrate an instance where spatial filtering employed for the compression of dynamic range will result in a realistic perception of relative contrast.

Higgins, K. E., and E. J. Rinalducci, Suprathreshold intensity-area relationships: a spatial Broca-Sulzer effect. Vision Research 1975, 15, 129-145.

Key Words: Intensity-area thresholds; spatial Broca-Sulzer

Three experiments are reported in which a brightness-matching procedure was used to determine the form of the foveal intensity-area relationship at varying suprathreshold levels. With two exceptions, the results of these experiments were consistent with previous threshold-level investigations of the intensity-area relationship. First, the nominal degree of spatial summation at the smallest stimulus size (less than 2 to 3 ft) consistently exceeded that predicted by Ricco's law at all visibility levels. However, further analysis indicated that this "supersummation" phenomenon is more than likely attributable to calibration errors introduced by diffraction. Second--and more important--at the higher suprathreshold levels the coefficient of spatial summation becomes negative between 3 and 6 ft, indicating that brightness decreased with increasing stimulus size. This effect was termed the "spatial" Broca-Sulzer effect by analogy to its more familiar temporal counterpart. The third experiment indicated that the form of the suprathreshold intensity-area relationship depends, to some extent, on the size of the standard stimulus used in the brightness-matching task.

CIG Implications: These results indicate that in most practical situations the contrast management procedures suggested for near-threshold stimuli may also accurately represent the natural relative contrast among objects within the display's limited dynamic range. Further research is required to clarify this issue.

Hood, D. C., T. Ilves, E. Maurer, B. Wandell, and E. Buckingham. Human cone saturation as a function of ambient intensity: a test of models of shifts in the dynamic range. Vision Research, 1978, 18, 983-993.

Key Words: Adaptation; dynamic range

Cone saturation refers to the fact that an intensity (the saturating intensity) of a flash can be found such that the cone system cannot detect increments upon this flash no matter how intense these increments are made. By making assumptions which relate both the psychophysically obtained threshold and saturating intensities of the flash to a supposed physiological response, models describing the shifts in the dynamic range can be tested. The present study examines the effects on threshold and saturation produced by various steady adapting intensities. The data are fit by a model incorporating changes in both the semisaturation constant of the system and the maximum response elicited by a flash.

CIG Implications: This article is relevant to the problems associated with the limited dynamic range of simulator displays. Since the visual system tends to be more sensitive to spatial and temporal changes than to the absolute level of stimulation or brightness, a realistic perception can be achieved if the relative contrast among real-world objects is accurately represented within the display's much more limited dynamic range. This can be done by developing a contrast compression algorithm that matches the compression accomplished by the visual system. The model presented in this article should provide a sound basis for such an algorithm.

Kulikowski, J. J. Effective contrast constancy and linearity of contrast sensation. Vision Research, 1976, 16, 1419-1431.

Key Word: Apparent contrast

Apparent contrast of gratings and edges was evaluated either by matching the contrast of an adjustable pattern to a reference contrast or by subjectively setting a fraction of the reference contrast. In the matching task, patterns appeared to have the same contrast when their suprathreshold contrasts (physical minus threshold) were equal. This result means that there was effective contrast constancy of various patterns of high contrasts, since at these levels large just-noticeable differences in contrast exceed the differences in contrast thresholds.

CIG Implications: Appropriate relative contrast within a display system's limited dynamic range may be modeled from the eye's contrast sensitivity function for both threshold and suprathreshold contrast levels.

Mansfield, R. J. W. Brightness function: effect of area and duration. Journal of the Optical Society of America, 1973, 63, 8, 913-923.

Key Words: Brightness; lumination; Broca-Sulzer

The dependence of perceived brightness on flash luminance and duration was determined for dark-adapted observers for various target sizes, retinal locations, and wavelengths. In the first series of experiments, observers made magnitude estimations of the brightness of flashes of varying luminance and duration. Perceived brightness varied as a power function of luminance with simple fractional exponents: 1, (1/2), (1/3). The exponents for brightness depend upon both target size and flash duration. The second series of experiments determined how the Broca-Sulzer brightness enhancement shifts to briefer or longer durations with changes of luminance. Observers adjusted the duration of constant-luminance flashes to produce a maximally bright flash. The flash duration producing maximum brightness varied as a power function of luminance with simple fractional exponents: (1/2) for point sources and (1/3) for extended sources. The regularity of the exponents suggests that a simple mechanism underlies the encoding of brightness information in the dark-adapted state.

CIG Implications: Relevant for the development of algorithms for the compression of dynamic range as a function of stimulus color, size and duration. Such algorithms are intended to produce the perception of realistic dynamic range within the limits of the display.

Marks, L. E. Brightness as a function of retinal locus in the light-adapted eye. Vision Research, 1968, 8, 525-535.

Key Words: Apparent brightness; relative brightness

Apparent brightness was measured by the method of magnitude estimation as a function of three parameters: luminance of the target, locus of stimulation, and level of light adaptation. For any given level of light adaptation, brightness grows as a power function of luminance and thereby conforms to the general psychophysical law proposed by S. S. Stevens.[*] The exponent of the power function does not appear to vary appreciably from one retinal locus to another. From the brightness functions it can be shown that a 1° white target of constant luminance appears brightest in the fovea; its brightness decreases steadily as the locus of stimulation is made more and more eccentric. Relative sensitivity (reciprocal of luminance at threshold) also decreases with distance from the fovea, except at low levels of light adaptation where sensitivity is greatest at about 5°.

CIG Implications: The data are relevant for the simulation of the relative contrast among elements of the visual scene within a display system's limited dynamic range. Appropriate contrast levels can be set in the data base by using the power function once the system's average brightness or adaptation level has been calculated. This strategy allows the determination of relative contrast for all retinal locations.

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[*] Stevens, S. S. Is There a Quantal Threshold? in Rosenblith, W. A. (Ed.), Sensory Communication. New York: Technology Press and Wiley, 1961.

Marks, L. E. Visual brightness: some applications of a model. *Vision Research*, 1972, 12, 1409-1423.

Key Words: Brightness; areal summation

Several models have postulated networks analogous to electrical filters in order to account for neurophysiological and psychophysical behavior of the visual system. A filter system that contains inhibitory feedback can be used to account for the cube-root relation that typically obtains between judged brightness and intensity of light flashes. Elaboration in terms of lateral facilitation and lateral inhibitory feedback enables the model to account for differences among brightness-intensity functions measured at different retinal loci. This type of elaboration may also help to account for the way brightness depends on stimulus area.

CIG Implications: The model presented in this study can be useful in efforts to develop algorithms that simulate the realistic appearance of relative brightness within a display's limited dynamic range.

Owens, D. A., and H. W. Leibowitz. Night myopia: cause and a possible basis for amelioration. American Journal of Optometry and Physiological Optics, 1976, 53, 709-717.

Key Words: Night vision; myopia

The relationship between night myopia under simulated night driving conditions and the dark focus of accommodation was examined. Over a range of luminance and contrast conditions typical of the night driving situation, college-age subjects accommodated to about one-half the difference between a distant simulated road sign and their individual dark focus. Subsequent laboratory and field experiments demonstrated that 1) a negative correction equal to half the value of the dark focus resulted in night visual performance that was significantly improved over that for normal or full dark-focus correction, and 2) greater improvements in performance were obtained for subjects who exhibited a relatively near dark focus.

CIG Implications: The illuminance of daylight scenes in a simulator display is considerably below that present in actual daylight. The reduced illuminance may result in a shift towards resting accommodation levels which are inappropriate for normal daylight viewing, and may decrease the amount of positive transfer between the simulator and actual flight conditions.

Sullivan, G. D., and M. A. Georjeson. The missing fundamental illusion: variation of spatio-temporal characteristics with dark adaptation. Vision Research, 17, 977-981.

Key Words: Craik-O'Brien illusion; dark adaptation; contrast sensitivity

When the fundamental frequency of a square wave is filtered out, a scalloped spatial luminance profile remains. At low spatial frequencies and low contrast the perception of a square remains unchanged when the fundamental frequency is missing--a phenomenon known as the missing fundamental version of the Craik-O'Brien illusion (Cornsweet, 1971).* This article presents a clear description of the conditions under which this illusion is observed.

CIG Implications: This illusion represents an example of a filtered or differentiated display that maintains the apparent relative contrast of an unfiltered display. It is relevant for dynamic range compression algorithms discussed in Section 2.

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*Cornsweet, T. Visual Perception. New York: Academic Press, 1970.

Thomas, J. P. Threshold measurements of Mach bands. Journal of the Optical Society of America, 1965, 55, 521-524.

Key Words: Mach band thresholds; dynamic range

Thresholds for Mach bands were obtained by filtering discontinuous luminance gradients until the bands disappeared. Visibility was related to two properties of the stimulus discontinuity at which the bands were seen: the change in the rate of change of luminance with respect to distance, and the luminance at the discontinuity. The former clearly affects visibility. The latter also appears to affect visibility, but its influence was not always demonstrable. Light and dark bands are independently perceived. Light-band thresholds vary with exposure duration according to Bloch's law.

CIG Implications: Relevant for dynamic range compression algorithms. Mach bands demonstrate the visual system's greater sensitivity to relative contrast than to the absolute level of illumination.

Walker, J. T. Brightness enhancement and the Talbot level in stationary gratings. Perception and Psychophysics, 1978, 23, 356-359.

Key Words: Subjective brightness estimation; Talbot's Law

At low spatial frequencies, the perceived brightness of the light phase of a stationary square-wave grating is greater than the brightness of a solid field of equal physical luminance. That increase in the perceived brightness of a grating at low spatial frequencies is analogous to the brightness enhancement observed in a flickering light at low temporal frequencies. At or above the critical spatial frequency--the visual resolution threshold--the brightness of a grating is determined by its space-average luminance, just as the brightness of a flickering light at or above the critical flicker frequency is determined by its time-average luminance in accordance with Talbot's law. Thus, Talbot's law applies in the spatial as well as the temporal domain. The present study adds to the evidence that temporal and spatial frequency play analogous roles in some aspects of brightness vision.

CIG Implications: Relevant for controlling the apparent brightness or contrast of objects within the limited dynamic range of a simulator display. This study provides another demonstration that the visual system is more sensitive to changes in illumination than to the absolute intensity of stimulation. In this case apparent brightness is scaled in terms of spatial frequency or changes in illuminations in the spatial domain. Thus algorithms for the compression of dynamic range should incorporate spatial frequency changes.

B.4 DIRECTIONAL ILLUMINATION EFFECTS

The absence of directional illumination in current CIG systems contributes to the unrealistic appearance of the display. The articles discussed in this subsection describe the basic physical properties of directional illumination, e.g., surface reflection, shadows, and glare. These data are needed to incorporate directional illumination into the data base.

Fry, G., and M. Alpern. The effect of a peripheral glare source upon the apparent brightness of an object. Journal of the Optical Society of America, 1953, 43, 189-195.

Key Words: Peripheral glare; apparent brightness

The decrease in perceived brightness of a foveal test object produced by a peripheral glare source can be accounted for in terms of a veiling luminance produced by stray light falling on the fovea. The same effect can be produced by an artifical patch of veiling luminance superimposed on the test object. The effect of increasing the angle between the glare source and the test object is equivalent to that of reducing the brightness of the glare source in accordance with the stray light hypothesis. The measured amount of veiling luminance conforms to that found by previous investigators. The changes in brightness that occur immediately following the onset of a peripheral glare source as well as the changes which occur following removal of the glare source can all be accounted for in terms of the veiling luminance produced by stray light falling on the fovea.

CIG Implications: The veiling glare that is normally produced by strong directional illumination sources (e.g., the glare of direct sunlight) or the light scattering caused by the windscreen are not present in current CIG displays. This article presents data describing the perceptual effects of glare and provides the basis for developing algorithms to simulate these effects.

Legge, G. E., M. A. Cohen and C. F. Stromeyer. Spatial-freuqency masking with briefly pulsed patterns. *Perception*, 1978, 7, 161-166.

Key Words: Spatial frequency; masking

Spatial-frequency masking was studied with briefly pulsed (25 msec) vertical gratings. The mask was a noise grating, and the test pattern was a sinusoidal grating. A low-frequency band of noise masked a low- but not a high-spatial-frequency test grating when the patterns were presented simultaneously. A high-frequency band of noise did not make a low-frequency test grating when the patterns were presented simultaneously or when the mask was presented after the test pattern (backward masking). Masking was observed, however, when the mask or test pattern was of a high enough contrast that the stimuli had nonlinear distortion and thus produced DC shifts of the field luminance.

CIG Implications: In actual flight conditions large and abrupt changes in the level of illumination can occur. For example, such changes will occur when moving in and out of the sunlight because of patchy cloud cover. Also reflections from highly reflective surfaces will cause an abrupt and short-lived elevation of illumination. Under these conditions masking may result in an impairment of the detection and identification of patterns in the darker field of illumination. At present none of these effects are incorporated in simulator displays.

Overington, I. Vision and acquisition. London: Pentech Press, 1976.
Key Word: Survey of visual research

The purpose of this book is to provide, in one volume, a survey of basic and applied research relevant to practical problems in the visual acquisition of information. The book deals with a wide range of applied problems but does not directly discuss the issues involving flight simulators in depth. Nevertheless, this volume represents the most current single collection of research that may be applied to CIG problems as indicated below.

CIG Implications:

1) Chapter 3 presents the few studies describing the variability of visual performance both within and between individuals. This information is quite necessary for selecting the stimulus threshold values in the data base that are most appropriate for a range of individual abilities.

2) Chapter 4 surveys all the major stimulus variables affecting detection thresholds, while chapter 5 covers a comparable portion of relevant data on recognition thresholds and acuity. Both these sections cover the basic information required for the implementation of more effective contrast management.

3) Chapters 6 and 7 survey attempts to model human visual performance and may prove useful for the development of contrast management algorithms.

4) Chapter 14 presents physical data on surface reflection which should prove quite useful in efforts to add directional illumination in CIG systems.

5) Chapters 15 and 16 survey the basic physical effects that the atmosphere has on the propagation of light. The data are presented in a form appropriate for the addition of aerial perspective in simulators.

B.5 RASTER EFFECTS

In the displays examined, the CRT was magnified to the point where the raster structure was resolvable. The presence of a visible raster structure tends to mask or prevent the detection of small objects or fine patterns. The articles summarized in this subsection describe the conditions under which these masking effects impair the realism of CIG displays.

Burr, D. C. Acuity for apparent vernier offset. Vision Research, 1979, 19, 835-837.

Key Words: Vernier acuity; dynamic acuity

Observers viewed an apparently moving vertical bar that was displayed sequentially at a series of discrete positions on an oscilloscope face. When the plotting sequence was such that the upper half of the bar was always displayed slightly before the lower, the bar appeared to be broken and offset at the middle, with the upper segment leading the lower (although they are actually displayed at identical horizontal positions). Acuity for detecting this illusionary offset is very fine; indeed, almost as fine as that for detecting real offsets. It is further shown that such an offset can be detected only if the bars are seen to be in motion.

CIG Implications: An interlaced raster structure may produce illusionary breakup of the components of moving objects. The small time delay between the two parts of an interlaced raster scan is within the range that the visual system can sometimes detect as a spatial displacement; e.g., at low update rates a double image of a small moving object may result.

De Valois, K. K. Spatial frequency adaptation can enhance contrast sensitivity. Vision Research, 1977, 17, 1057-1063.

Key Words: Adaptation; contrast sensitivity; enhancement

Adaptation to a high-contrast sinusoidal luminance grating produces a temporary band-limited loss in sensitivity centered around the adaptation frequency. The decrease appears to be both narrower and more symmetrical than earlier reports suggest. The effect falls to zero by f ± 1 octave and is not reliably present from f ± 1 octave to f ± 2 octaves. Enhancement of contrast sensitivity occurs for frequencies further removed, peaking at about f ± 2-3/4 to 3 octaves. This suggests mutual inhibitory interactions among spatial-frequency-selective units of varying filter characteristics. Long-term practice produces significantly higher contrast sensitivity functions and narrower bandwidths of the adaptational sensitivity loss.

CIG Implications: Adaptation to the spatial frequency of a display's raster structure occurs within several minutes of viewing time. While adaptation produces an unrealistic decrease in sensitivity to visual patterns of similar frequency and orientation, the sensitivity to dissimilar spatial frequencies is spuriously increased. These problems can be attenuated by demodulating the raster.

Erickson, R. A., and J. C. Hemingway. Visibility of raster lines in a television display. Journal of the Optical Society of America, 1970, 60, 700-701.

Key Words: Image formation; raster lines; resolution

The discrimination of raster line orientation was evaluated during the display of air-reconnaissance photographs and triangles and circles of differing sizes. Discrimination decreased with viewing distance for all display types, especially when the raster lines subtended less than 0.3' visual angle. Performance for horizontal and vertical orientations was superior to that for oblique orientations.

CIG Implications: Raster lines are somewhat less visible if they have an oblique orientation instead of the usual horizontal or vertical orientation. This decrease in visibility occurs because the human visual system is less sensitive to patterns with oblique orientations. Furthermore, physical resolution of the CRT is somewhat higher for patterns obliquely oriented to the raster lines. Thus, an oblique orientation of the raster lines will decrease their visibility and increase the CRT resolution in the horizontal and vertical orientation where the visual system is most sensitive.

May, J. G. Chromatic adaptation of orientation and size specific perusal processes in man. Vision Research, 1972, 1509-1517.

Key Words: Adaptation; orientation; spatial frequency

This study involved two experiments to investigate the effects that adaptation to chromatic gratings of (a) different orientation and (b) different spatial frequency has on the threshold for chromatic test gratings of the same or different wavelengths, orientations, and spatial frequencies. Thresholds were elevated by adaptation to gratings that were of the same wavelength and orientation or the same wavelength and spatial frequency as the test grating. Adaptation to gratings that were of different wavelength and/or orientation or different wavelength and/or spatial frequency from the test grating did not affect thresholds significantly. In addition, homogeneous chromatic adapting fields were used and it was found that the thresholds for chromatic test gratings were not significantly elevated by such adaptation. These results were in general agreement with previous studies of orientation-specific and size-specific visual mechanisms, and it was concluded that these findings offer corroboration of the McCollough effect using threshold measures.

CIG Implications: The decreased visibility of visual patterns caused by adaptation to a display's raster structure is specific to color, spatial frequency and orientation. These unrealistic effects can be reduced only by decreasing the visibility of the raster lines through demodulation or other means.

Pantle, A. Visual information processing of complex imagery. Aerospace Medical Research Laboratory Technical Report AMRL-TR-74-43.

Key Word: Harmonic analysis of visual imagery

An analysis of extant literature reveals a large body of experimental evidence supporting the concept that the human visual system performs a two-dimensional harmonic analysis of visual stimuli. It also reveals a smaller body of evidence that seems to contradict this concept. Experiments performed in this report propose a resolution of these apparent contradictions, and show how existing concepts must be slightly modified to include changes in the kind of harmonic analysis performed. Three kinds of analysis, representing increasingly fine spatial-frequency resolution, seem to quantify human performance at many form-perception tasks; the kind of analysis performed depends on the task. A single plot showing the masking effect of one spatial frequency on another promises great utility in target acquisition and detection studies, camouflage designs, and designs for optimal man/machine interfaces.

CIG Implications: The ability to describe human visual perception in terms of Fourier analysis is important because such a formulation is quite amenable to the computational procedures required in CIG systems. Furthermore, the analysis as treated in this report has special relevance for predicting the masking effects the raster structure will have on the various types of visual patterns represented on the display.

Pollehn, H., and H. Roehrig. Effect of noise on the modulation transfer function of the visual channel. Journal of the Optical Society of America, 1970, 60, 842-846.

Key Words: Modulation transfer function; noise thresholds

The effect of noise on the modulation transfer function was studied by means of threshold measurements. White noise and 1/f noise of various levels and different cutoff frequencies were displayed on a television screen together with a sinusoidally modulated bar pattern. The signal-to-noise threshold necessary for perception was measured as a function of the spatial frequency of the bar pattern. This signal-to-noise threshold, which is strongly dependent on the bar-pattern frequency, is also dependent on the rms value and the frequency distribution of the noise as well as the difference between the bar-pattern frequency and medium frequency of the noise. An attempt was made to explain the results by visual observation of the bar pattern in the presence of narrow-bandwidth noise.

CIG Implications: The masking effects of any noise in a display system will depend on the spatial frequency of both the noise and the target. Targets that have spatial frequencies near the medium frequency of the noise will be harder to detect than any other targets.

Stromeyer, C. F., and B. Julesz. Spatial-frequency masking in vision: critical bands and spread of masking. Journal of the Optical Society of America, 1972, 62, 1221-1232.

Key Words: Modulation transfer; masking

Vertical sinusoidal gratings were viewed in masking noise composed of vertical stripes spread along the horizontal direction. Masking functions were obtained while varying the grating frequency relative to various one-octave-wide bands of noise. These functions closely resemble curves derived from previous experiments on adaptation to gratings. Masking was also measured as a function of the width of a band of noise centered on the grating frequency. Masking increased as the band was widened up to approximately ±1 octave; masking did not increase further when the band was widened beyond this range. The results demonstrate that a grating is masked only by noise whose spatial frequencies are similar to the grating frequency. The experiments provide further indication of the existence of channels in the visual system that are selectively tuned to different spatial frequencies.

CIG Implications: Raster lines will tend to selectively mask visual patterns containing similar spatial frequencies and orientation. Thus, the detection of patterns consisting of spatial frequencies between about 6 to 10 cycles/degree with a horizontal orientation will be impaired. This impairment is caused by the properties of the visual system and not by the aliasing associated with the raster structure.

Tangney, J., N. Weisstein, and K. Berbaum. Masking independent of both separation and spatial frequency. Vision Research, 1979, 19, 817-823.

Key Words: Forward masking; spatial frequency; distribution

The brief presentation of a single dark bar lowered the apparent contrast of a subsequently flashed patch of grating regardless of the spatial separation of the two patterns (up to 4° of visual angle). This forward-masking effect occurred when the bars of the two patterns were identically oriented, but not when their orientation differed by 90°. Such an orientation-selective interation effect between widely separated patterns could result from Fourier-like distribution of visual information, but the magnitude of the masking effect is not affected by the similarity of the patterns in the Fourier domain. Pattern coding by local features might explain only the orientation specificity and the lack of frequency tuning, while pattern coding by Fourier features might explain only the orientation specificity and the distribution effect. Therefore, neither class of features completely describes the initial coding of visual patterns.

CIG Implications: Shows the existence of orientation-specific masking for spatially nonoverlapping patterns. Indicates that raster lines may produce masking effects even in areas of the display where their visibility is negligible.

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Tolhurst, D. J. Separate channels for the analysis of the shape and the movement of a moving visual stimulus. Journal of Physiology, 1973, 231, 385-402.

Key Words: Adaptation; spatial frequency channels; temporal modulation

The effects of temporal modulation on the properties of spatial frequency channels were determined using adaptation. Adapting to drifting sinusoidal gratings caused threshold elevation that was both spatial-frequency and direction specific. Little systematic difference was found between the bandwidths of the elevation curves for drifting and stationary gratings. It was confirmed that adaptation fails to reveal channels at low spatial frequencies when stationary gratings are used. However, channels were revealed at frequencies at least as low as 0.66 c/deg when the test gratings were made to move. The fact that these channels are only minimally adapted by stationary gratings confirms their dependence on movement. The existence of movement-sensitive channels at low spatial frequencies explains the well known observation that temporal modulation increases the sensitivity of the visual system to low spatial frequencies.

Temporal modulation effectively revealed these channels only when the flicker or movement of the test patterns was apparent to the observer. Only at low spatial frequencies did patterns modulated at low rates actually appear to be temporarily modulated at threshold. At higher spatial frequencies, these patterns were indistinguishable from stationary patterns until the contrast was above the detection threshold. It was suggested that the movement-sensitive channels are responsible for signaling the occurrence of movement and that the channels at higher spatial frequencies give no information about temporal changes.

CIG Implications:

1) Adaptation to the display's raster structure will raise detection and identification thresholds to patterns with similar frequency components. These adaptation effects can be reduced if the raster structure can be demodulated in space and/or time.

2) Because direction-specific adaptation to movement may not be simulated properly at low update rates, there will be less positive transfer of training to actual flight conditions.

Tolhurst, D. J., and L. P. Barfield. Interactions between spatial frequency channels. Vision Research, 1978, 18, 951-958.

Key Words: Spatial frequency; masking

The sensitivities for sinusoidal gratings of various spatial frequencies were determined by a two-alternative, force-choice technique. The effects of the simultaneous presence of a grating of 4.25 c/deg on sensitivity were examined. The effects of prolonged adaptation to the same grating were also examined. When the testing frequency was close to the masking or adapting frequency, threshold was elevated; when the frequencies differed by 1 to 2 octaves, the threshold was lowered (sensitivity was increased).

CIG Implications: These data indicate that spatial frequencies close to that of the raster will have elevated thresholds, and those 1 to 2 octaves removed will have lowered thresholds.

B.6 COLOR

The color represented in CIG displays is often described as too vivid and cartoonlike. The following summarized articles are relevant to the reduction of this problem. Other articles in this subsection describe how color may lessen the masking effects produced by a visible raster structure.

Ellis, S. R. Orientation selectivity of the McCollough effect: analysis by equivalent contrast transformation. Perception and Psychophysics, 1977, 22, 539-544.

Key Words: Orientation; color; McCollough effect

Using a color-cancellation technique, the strength of the McCollough effect was measured in units of excitation purity. The strength was studied both as a function of the contrast of the adapting gratings and as a function of the angle X between the axes of the test and the adapting gratings. Results were well described as a linear function of the contrast of the adapting gratings and as a cos(2X) function of the angle. Both functions were combined to express an equivalent contrast transformation which converts the measurements of orientation tuning into a unit comparable to that used for other kinds of orientation-specific aftereffects. The orientation tuning was found to be very broad with a half-width at half amplitude of approximately 27°. This estimate is considered to be a substantial underestimate of the actual tuning of the aftereffect's substrate.

CIG Implications: The masking effects caused by adaptation to the raster structure will have some degree of specificity to color as well as to spatial frequency and orientation. The color specificity should occur only in those situations where some portion of the display is one color for a considerable length of time. This problem can be attenuated by demodulating the raster scan.

Indow, T. Scaling of saturation and hue in the nonspectral region. Perception and Psychophysics, 1978, 24, 11-20.

Key Words: Color; saturation

The saturation of two nonspectral hues, magenta and violet, and the hue shift between red and blue through the nonspectral region were both scaled by two methods--equisection to produce a difference scale (ψ_D) and ratio judgments to produce a magnitude scale (ψ_M). The colored stimuli were viewed through apertures in a dark surround, with the luminance kept constant at one of three levels--0.5, 2.15, and 12.6 cd/m^2. The results were as previously found with saturation and hue shift between two adjacent primary hues in the spectral region. That is, with exponents larger than unity, ψ_D was linear with colorimetric purity for the saturation of magenta or violet and with the mixture ratio of red or blue for the hue shift, and ψ_M was a power function of colorimetric purity for the saturations and with the mixture ratio for the hue shift. The present results were combined with previous results to give the change of parameters for saturation functions over the entire hue circle.

CIG Implications: Useful for the selection of color saturations to be represented in the data base.

Lovegrove, W. Inhibition between channels selective to contour orientation and wavelength in the human visual system. Perception and Psychophysics, 1977, 22, 49-53.

Key Words: Orientation; color; channel inhibition

Recent studies have demonstrated inhibition between channels selective to contour orientation in the human visual system. On the basis of adaptation studies, it has also been suggested that the human visual system contains channels jointly responsive to both contour orientation and wavelength. The present paper investigates inhibition between channels. Two experiments demonstrated that, with simultaneous presentation of a center vertical target grating and a concentric surround grating, the threshold and the apparent orientation of the center grating depended on the relative orientations of the two gratings and also on whether they were viewed in the same or in different colored light. Color selectivity in both experiments was found across a wider range of angular separations than has generally been reported for successive presentation of the two stimuli. These results suggest inhibition between channels selective to combinations of contour orientation and wavelength in the human visual system.

CIG Implications: The masking produced by a visible raster will be selective for color as well as spatial frequency. Thus, masking caused by the raster structure may be less for color displays than for black and white displays. This effect partly justifies the additional cost of color displays.

Watanabe, A., T. Mari, S. Nagata, and K. Hiwatashi. Spatial sine-wave
responses of the human visual system. Vision Research, 1968, 8,
1245-1263.

Key Words: Modulation transfer; frequency response

This article presents the sine wave response of the human visual system measured under various objective and subjective conditions using a monochrome television display system.

Generally, the sine wave response curve of the visual system represented the shape of a bandpass filter, and the maximum contrast sensitivity was observed in the range of 0.04 to 0.1 line/min of arc.

The response in the high spatial frequency region was affected by the orientation of the sine wave pattern, and became minimum when the pattern was tilted 45°. The spatial frequency bandwidth of the response increased with the rise of both the contrast level and the average luminance level of the pattern. The response increased remarkably in the high frequency region when the contrast level rose, and a small dip appeared in the middle frequency region when the average luminance level rose above 30 ft-L. The cutoff frequency in the high frequency region rose monotonically with increase of the observation distance up to about 5 m.

The reduction of the pattern size largely decreased the response in the low frequency region. The limitation of the stimulus duration resulted in the reduction of the response, especially in the medium frequency region. The white stimulus exposed just before the presentation of the sine wave pattern also reduced the sine wave response.

When the vertically striped sine wave pattern drifted horizontally with constant velocities, the response in the high frequency region decreased and the specific velocity was found where the response in the low frequency region became maximum and the specific velocity was a function of the spatial frequency.

Coarse stabilization of the retinal image brought about a reduction of response, and the contrast threshold rose from 5 to 15 dB in the measurement in the low frequency region.

No remarkable change of response according to the spectral distribution of the pattern was observed, except for a slight reduction of response to blue patterns.

CIG Implications: This article contains a large portion of the data required to implement the suggestions for more effective contrast management discussed in Section 2. Contrast thresholds were determined as a function of spatial frequency, orientation, field of view, average luminance level, temporal modulation and color. The findings show that contrast management for color is basically the same as for white light if the differing spectral sensitivity of the eye is taken into account.

Willmer, E. N. Subjective brightness and size of field in the central fovea. Journal of Physiology, 1954, 123, 315-323.

Key Words: Subjective brightness; foveal threshold; foveal wavelength sensitivity

For measurements of threshold, the relationship between the size (i.e., area) of the central foveal field stimulated and the luminance of the field is different from what it is for the assessment of brightness by comparison with another field of constant size and luminance.

When determining the threshold of visibility in the foveal center, measurements of the relationship between area and luminance are essentially independent of wavelength on changing the size of the stimulated field. This is not true when measuring brightness against a standard field in this region of the retina, because blue fields are found to behave differently than red or yellow fields.

CIG Implications: Relevant data for the development of dynamic range compression algorithms. To maintain real-world relative contrast within the display's limited dynamic range, the fact that the visual system is less sensitive to blue light than to other wavelengths must be taken into account.

B.7 LEVEL OF DETAIL

The articles discussed in this subsection primarily concern the aliasing effects commonly observed when a switch is made from one level of detail to another. Some of the articles also describe texture perception--a topic that is relevant to level of detail when an attempt is made to add texture to CIG displays.

Braddick, O. The masking of apparent motion in random-dot patterns. Vision Research, 1973, 13, 355-369.

Key Words: Apparent motion; masking

Two random-dot patterns were alternated to give apparent motion of a central square region. The appearance of the moving square could be masked by exposing a uniform light field in the interval between the patterns. This masking effect 1) was not found when the patterns and blank field were exposed to different eyes; 2) was of similar magnitude when a visual noise field was used; 3) was greatest when the masking field luminance was slightly greater than that of the patterns, declining for brighter fields; 4) was not produced by light adaptation if the interval itself was dark; 5) could not be accounted for by the reduction in apparent pattern contrast; 6) was greatest when the masking field was exposed early in the interval. Three hypotheses are discussed: 1) that this masking of motion is an aspect of a more general masking of the patterns, 2) that it is due to stimulation of motion detectors by the masking field, and 3) that it is due to erasure of briefly stored information. The first hypothesis is rejected.

CIG Implications: All dynamic CIG displays depend on the phenomenon of apparent motion to represent the perception of real motion. This article adds to our knowledge of apparent motion by describing the conditions that mask its perception. Further research is required to determine whether this masking also occurs for real motion and whether it represents a significant problem for CIG displays.

Breitmeyer, B. G. A relationship between the detection of size, rate, orientation and direction in the human visual system. Vision Research, 1973, 13, 41-58.

Key Words: Motion perception; size and shape relationships

Differential increment thresholds for stationary gratings of variable spatial frequency and for moving patterns of variable velocity following adaptation to either of two velocities (2.5 and 6.5 deg/sec) or to either of two spatial frequencies (1.5 and 4.5 c/deg), respectively, indicate that the human visual system contains units of analysis which respond selectively to stimulus size and velocity. A distinction between two types of units, speed and velocity (i.e., speed and direction) analyzers, was established. Under conditions of systematically varied background illumination levels, correspondingly systematic changes in the size velocity preference of the hypothesized analyzers occurred, suggesting that the unit impulse response (i.e., the response of a unit to a pulsed stimulus presentation) determines the analyzers' size-velocity preference. The preferred velocity, v, and spatial frequency (size), f_s, were shown to be relatable by the formula $f_s vi = 1$, where i is the interval between the onsets of the primary and secondary excitatory discharges of the unit impulse response.

CIG Implications: The data are relevant for determining update rates that will produce a natural perception of motion depending on the size, rate, orientation and direction of stimulus movement.

Breitmeyer, B. G., and L. Ganz. Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing. Psychological Review, 1976, 83, 1-32.

Key Words; Transient vision model; sustained vision model

The sustained/transient model presented here conceptualizes the visual system as comprising two parallel and semi-independent channels which are in a complementary relationship. The transient system is functionally characterized by high temporal resolution, short latency, and relatively low spatial resolution, and comprises part of an "early warning system" that orients an organism and directs its attention to locations in visual space that potentially contain novel pattern information. This pattern information is subsequently analyzed by the sustained system, which is characterized by high spatial resolution, long latency, and long integration time. High-acuity tasks, such as the recognition of small forms and high-resolution stereoacuity, would accordingly require a longer perception time than low-acuity tasks.

One of the design problems inherent in the sustained system is that its long integration time permits strong proactive or forward masking by integration between successive fixations of the visual world. This could be solved simply by increasing the duration of the fixation or intersaccade interval. The price, however, would be a reduction in the rate of visual information processing.

This design problem is to some extent overcome by the existence of inhibitory actions of the transient system on the sustained system. The interaction between the transient and sustained systems is illustrated by the following sequence of events. An organism is fixating and analyzing a given spatial pattern. The sustained channels are slowly accumulating the pattern information. Suddenly a novel object appears in the periphery of the visual field (e.g., by moving). The novel object stimulates transient neurons, presumably in the superior colliculus, which command a reorientation of head and eyes so as to foveate the novel object. The command to move the eyes is realized in a saccade. Concomitantly, transient channels in the retino-geniculo-cortical pathway inhibit sustained channels at various levels of the visual system and thus help to terminate the long integration within sustained channels which would otherwise persist into the next fixation period.

CIG Implications:

1) Perception of small detailed forms requires a substantial period of temporal integration. Therefore, small levels of detail that would be in the visual field for very short time periods will not be detected and need not be displayed.

2) Transient stimuli that appear in the periphery can interrupt the processing of foveal vision. Therefore, it is important to eliminate the abrupt appearance of objects in simulator displays that are caused by inappropriate contrast management.

Breitmeyer, B., R. Love and B. Wepman. Contour suppression during stroboscopic motion and metacontrast. Vision Research, 1974, 14, 1451-1456.

Key Words: Masking; stroboscopic motion

Findings of visual contour masking obtained when two stationary and spatially separated stimuli are presented briefly and successively in time indicate that the contour masking typically observed while viewing a stimulus in real movement also occurs while viewing a stimulus in stroboscopic movement. Additional results indicate that the loss of detailed contour information attending stroboscopic movement may contribute to, though not constitute, the contour suppression effects observed in metacontrast.

CIG Implications: The suppression of contours or sharp edges in stroboscopic or real movement implies that these details need not be presented for objects in motion. If so, computing time might be reduced and some of the aliasing effects observed for small levels of detail during motion might be attenuated.

Caelli, T., and D. Finlay. Frequency, phase, and color coding in apparent motion. Perception, 1979, 8, 59-68.

Key Word: Apparent motion

Results are presented which indicate that the known spatiotemporal limits for apparent motion are consistent with the motion being sinusoidal as a result of filtering. The filter model was investigated by determining how two such motions interact as a function of their relative temporal phase differences. This determination was made by inducing two independent motions from complementary colored event pairs. The results indicated critical phase limits for perceiving the two motions (red and green) which were consistent with the frequency specificity of the effect. The results are discussed within the framework of a filtering process for the perception of apparent motion.

CIG Implications: The illusion of apparent movement is the means by which all simulator displays represent real continuous motion. Establishing that the apparent motion in complex CIG scenes can be described using the filter model developed in this study might prove useful for determining the realism of displayed information as a function of the update rate.

Fox, J., and J. E. W. Mayhew. Texture discrimination and the analysis of proximity. Perception, 1979, 8, 75-91.

Key Words: Texture discrimination; Marr theory; Julesz theory

A major theory of early visual processing considers a number of aspects of visual perception in great detail, including grouping and texture discrimination. New phenomena associated with texture discrimination are described and experiments reported which allow a preliminary comparison of this theory, as it applies to texture discrimination, with more established theories. One experiment produced results which are clearly consistent, but the ability of the theory to deal with additional data on region suppression is not established. The theory of the analysis of proximity relations proposed by Fox offers a broadly satisfactory account of many texture perception results, while relying on the more fundamental theory of primitive visual processes to deal with the remainder. A further attraction of proximity analysis is that it may shed new light on the classical paradox of symmetry perception. Some ways in which the preliminary proximity analysis model is incomplete are discussed, and it is concluded that development of the model may be profitable for theories of early visual processing.

CIG Implications: This article is relevant for attempts to add texture to simulator displays in order to enhance the perception of surfaces and other visual forms as a single object. The theories discussed may prove useful in the development of algorithms for simulated texture that optimize this goal.

Harvey, L.O., Jr., and M. J. Gervais. Visual texture perception and Fourier analysis. Perception and Psychophysics, 1978, 24, 534-542.

Key Words: Texture; modulation transfer

The relationship between the Fourier spectra (represented by four hypothetical visual channels sensitive to spatial frequencies) and the perceptual appearance of the textures was investigated. Thirty textures were synthesized by combining various spatial frequencies of different amplitudes. Twenty subjects grouped the textures into two, three, four, and five groups based on their similarity of appearance. The groupings were analyzed by means of linear discriminant analysis using the activity of the four channels as predictor variables. The groupings were also examined by multidimensional scaling, and the resulting stimulus configuration was canonically correlated with the channel activity. The results of both analyses indicate a strong relationship between the perceptual appearance of the textures and their Fourier spectra. These findings support a multiple-channel spatial-frequency model of perception.

CIG Implications: Over a broad range of conditions texture discrimination and detection can be described by the output of only four bandpass filters sensitive to different regions of the Fourier spectra. These findings offer a simple method for selecting textures that will enhance the perceptual segregation of different surfaces. Furthermore, the visual system's contrast sensitivity function can be used for controlling the appearance of texture components as a function of calculated distance.

Kulikowski, J. J., and D. J. Tolhurst. Psychophysical evidence for sustained and transient detectors in human vision. Journal of Physiology, 1973, 232, 149-162.

Key Words: Transient response; sustained/transient detectors

The sensitivity to temporally modulated sinusoidal gratings was determined. Two thresholds could be distinguished for the modulated gratings: the contrast at which flicker could be perceived and the contrast at which the spatial structure became distinct. The flicker detection threshold and pattern recognition threshold varied independently as functions of the spatial and temporal frequencies, suggesting that the two thresholds represent the activity of two independent systems of channels.

The channels detecting flicker prefer low and medium spatial frequencies. They have a pronounced decline in sensitivity at low temporal frequencies of sinusoidal modulation. They respond twice as well to gratings whose phase is alternated repetitively as to gratings turned on and off at the same rate. The channels responsible for the discrimination of spatial structure are most responsive at high and medium spatial frequencies. There is no decline in sensitivity at low temporal frequencies. These channels respond equally well to alternating and on/off gratings up to about 8 Hz. The temporal properties as revealed with sinusoidal modulation suggest that the flicker-detecting channels responsible for analyzing the spatial structure would give sustained responses. The responses of the two types of channels to alternating and on/off gratings confirm this suggestion.

CIG Implications: Because transient mechanisms of the visual system may not be stimulated realistically by dynamic simulator displays, positive transfer will decrease. This article gives some of the stimulus parameters that normally elicit a transient response. These parameters indicate that aliasing effects may be most visible when these signal distortions stimulate transient channels of the visual system.

Pantle, A. Adaptation to pattern spatial frequency: effects on visual movement sensitivity in humans. Journal of the Optical Society of America, 1970, 60, 1120-1126.

Key Words: Detection; spatial frequency dependence; visual movement

Human luminance thresholds were measured using a square-wave test grating (spatial frequency = 0.38 cycles/deg) moving at different speeds (from 0.0° to 22°/sec). A set of gratings of various spatial frequencies ranging from 0.00 (uniform field) through 23 cycles/deg provided different adapting patterns that were viewed prior to threshold determinations. The pattern of threshold elevations produced by the set of adapting gratings was different for different test-grating speeds. These results indicate that visual mechanisms with different spatial-frequency-tuning characteristics mediate the detection of a low-frequency grating when it is moved at different speeds. Also, results were obtained which suggest that the higher-harmonic components of a low-frequency grating contribute to its detection when it is moved at slow speeds.

CIG Implications: Adaptation to stimulus movement that is observed under normal viewing conditions may not occur in the simulator at low update rates. This deficiency may be particularly relevant to the movement of low spatial frequencies.

Richards, W., and T. B. Felton. Spatial frequency doubling: retinal or central? Vision Research, 1973, 13, 2129-2137.

Key Words: Spatiotemporal modulation; image doubling

When a field is sinusoidally modulated both in space and time, the spatial frequency of the pattern will appear doubled at temporal frequencies of 30 Hz and above. This paper discusses the possible anatomical locus of this phenomenon.

CIG Implications: This phenomenon may partly be the cause of the image-doubling of a string of runway lights that has been observed in some displays using update rates of 30 Hz. Unfortunately, little is known about the cause of either phenomenon at the present time.

Westheimer, G., and S. P. McKee. Perception of temporal order in adjacent visual stimuli. Vision Research, 1977, 17, 887-892.

Key Words: Temporal order; spatiotemporal interaction

For single short exposures, the temporal order of appearance of two adjacent stimuli in the human fovea can be correctly identified when one is delayed by as little as 3 msec. The threshold delay is almost unaffected by the length of the stimuli or their relative orientation, but depends critically on their separation, being minimal in the range 2 to 6 ft. Illusion of movement is a strong but not a necessary condition for detection of temporal order. In the conditions showing lowest thresholds, sensitivity is less with dichoptous viewing. Unilocular stimuli in opposite directions can be combined to yield a stereoscopic appearance. If the neural processing for such fine spaciotemporal comparisons does not occur in the retina, the results imply that retino-cortical transmission of the involved signals is exceedingly crisp and that cortical processing is more delicate if stimuli arise wholly in one eye.

CIG Implications: These fine temporal discriminations require update rates considerably beyond the range of current simulators. This fact partly explains why the breakup of contours due to aliasing is so easily detected. Aliasing can produce small and spurious changes in the position of contour segments from one frame to the next. These changes can produce distracting apparent movement that is well within the sensitivity of the visual system.

B.8 SURFACE DEFINITION

The research deals with information that is necessary and/or sufficient for accurate perception of surface orientation, size, and distance, and the observer's relative motion with respect to a surface. The problem is restricted to monocular displays presented on a two-dimensional surface. Research employing dynamic displays is more relevant to the topic than is research using static displays. The most promising line of research concerns the effectiveness of different types of texture gradients in perceiving distance, slant, and shape. Another important source of information is cast and attached shadow.

In CIG displays, perceived distance is often ambiguous. For example, the limited cues to distance available in a limited-information monocular display are often contradicted by the presence of flatness cues. The open problem is to determine how the perception of object sizes operates under these conditions. The size-distance invariance hypothesis, which contends that perceived size and perceived distance are inversely related, suggests that ambiguity of distance implies ambiguity of size. In fact, one interpretation of this hypothesis holds that the human visual system computes object sizes after perceived distance has been fixed. The available research investigates this hypothesis.

When contours appear in flat surfaces in CIG displays, different parts of the surface will often appear to be separated in depth. The illusion is sometimes strong enough to cause portions of the flat surface to appear to be floating above the ground. The literature search is concentrated into three areas relevant to this illusion: depth adjacency, figure-ground segregation, and chromostereopsis.

Darkened areas along the sides of surfaces in CIG displays seem to be interpreted by the visual system as shaded sides of raised surfaces. For example, if the areas along a runway's sides are darkened, the whole runway appears as an elevated surface. Another misperception of orientation occurs when the angles formed by surface contours are extremely acute or obtuse. Instead of appearing flat in these cases, the surface appears to be slanted away from the frontoparallel plane.

Beverly, K. I., and D. Regan. Evidence for the existence of neural mechanisms selectively sensitive to the direction of movement in space. Journal of Physiology, 1973, 235, 17-29.

Key Words: Motion perception; depth perception; binocular disparity; binocular vision

Subjects viewed an irregularly spaced pattern of dots with the left eye and a similar pattern with the right eye. The 2° central areas of each pattern were sinusoidally oscillated from side to side. When the left and right patterns were viewed in binocular fusion, the 2° central area generally appeared to oscillate in depth. Altering the relative amplitudes of oscillation of the left and right targets (i.e., left:right ratio) changed the direction of the line along which the target appeared to oscillate in three-dimensional space. By turning a logarithmic control potentiometer, the subject could vary the absolute amplitude of the retinal image movements without altering the left:right ratio. For a given left: right ratio, the oscillation amplitude of retinal disparity was varied until the subject was just able to see the target's oscillations in depth (depth threshold). Depth thresholds were determined over the complete range of left:right ratios. Adapted thresholds were measured after a 10-min adaptation to movement in depth. When the target appears to oscillate in a direction wide of one eye, the retinal image in that eye oscillates through a smaller distance than does the image in the other eye, but both oscillate in phase. When the target's direction of motion is directed to any point between the eyes, the two retinal image positions oscillate in antiphase.

The impressions produced by gazing at a stimulus target were as follows. At first the target's oscillations in depth were large, but they grew progressively smaller until after several minutes no movement in depth was visible. Although several minutes of adaptation were necessary to completely abolish the perception of movement in depth, a marked loss of sensitivity took place within the first few seconds of adaptation, especially for near-threshold adapting stimuli. There was a subjectively striking observation: If, after abolishing the perception of movement in depth by sufficient adaptation, the left:right ratio of the adapting stimulus were changing, then large excursions in depth immediately became visible. Only five different curves were needed to describe the elevations of threshold for depth movement produced by thirteen different adapting left:right ratios. The five curves can be summarized in terms of four hypothetical sensitivity functions, which could correspond to the neural mechanisms underlying visual sensitivity to depth movement. These mechanisms are tuned to the left:right ratio and might act as detectors of the direction of motion in three-dimensional space.

CIG Implications: These results strongly support the existence of dynamic binocular disparity cues to motion in depth which are distinct from static binocular disparity cues. Binocular disparity has long been held to be an ineffective cue to depth at far distances, but there is no reason to believe that dynamic binocular disparity, as described here, is not effective at far distances. A pilot in actual flight probably uses dynamic binocular disparity to perceive motion in depth. Of course, dynamic binocular disparity cannot be used under monocular conditions such as in CIG displays. Artificial depth cues probably will need to be provided in CIG displays to fill the deficit.

Beverly, K. I., and D. Regan. Separable aftereffects of changing-size and motion-in-depth: different neural mechanisms? Vision Research, 1979, 19, 727-732.

Key Words: Motion aftereffects; depth perception; motion perception; size change

The following aftereffects resulted from inspecting a square whose vertical edges moved towards each other with a ramping waveform: a static test square 1) appeared to be continuously expanding along the horizontal direction, and 2) appeared to be moving in depth. Each aftereffect was quantified by measuring the real rate of size change required to cancel it. Both aftereffects decayed exponentially, with the motion-in-depth aftereffect decaying at a slower rate. Because of the different decay rates, the two aftereffects could be seen separately.

In a previous study by the same authors, when a square whose vertical and horizontal edges moved towards each other with a ramping waveform so that the square changed size but not shape, a static test square appeared to move in depth, but no changing-size aftereffect resulted. A psychophysical model was proposed in which unidirectional motion filters feed a changing size filter that in turn feeds a motion-in-depth stage. Stated in simpler terms, feature dectectors in the visual system sensitive to moving edges signal the presence of an object changing in size, which results in a compelling impression of motion in depth. The impression of depth results despite the fact that the visual stimulus could be stationary and merely expanding or contracting itself.

CIG Implications: When a CIG display is in motion and under observer control, the changing size cue can give the observer a compelling impression of depth. Not only can objects take on depth and orientation in three-dimensional space, but the changing-size cue may also offer a cue to relative velocity of the observer with respect to surface objects. This dynamic depth cue may help to compensate for the paucity of static cues to depth in CIG displays.

Braunstein, M. L. Perception of rotation in figures with rectangular and trapezoidal features. Journal of Experimental Psychology, 1971, 91(1), 25-29.

Key Words: Perspective; contour angles; rotation perception

The figural basis for the effect of perspective changes on the accuracy of judgments of rotation direction was investigated. In a complete trapezoid, the presence of acute angles on one side and obtuse angles on the other is a necessary consequence of the inequality of the sides. In the present study, open forms varying in angles of contour convergence and relative extent of vertical contours were displayed in rotation about a vertical axis at five perspective levels. Contour angles dominated relative extent of vertical contours as a misleading cue to direction of rotation. Accuracy, averaged across perspective levels, was ordered primarily by angle relationships. Accuracy was greatest for forms containing right angles (even when the vertical contours were unequal) and lowest for forms in which one vertical contour was enclosed in acute angles and the other in obtuse angles (even when the vertical angles were equal). The side enclosed by the acute angle tends to appear closer throughout the rotation, while the side enclosed by the obtuse angle appears more distant.

CIG Implications: These results probably can be generalized to the case of static perception of slant. For example, if a field portrayed as a quadrilateral in a CIG display is also rectangular, it will tend to appear to lie flat on the surface. On the other hand, if the quadrilateral field contains acute and obtuse angles, the sides comprising the former may appear to extend from the frontoparallel plane toward the observer, while sides comprising the latter may appear to recede from the observer, forming a depression in the surface. There are two general ways to avoid this misleading cue to slant. The safest method is to use only right angles to define surface contours. A second method is to provide vertical cues to slant which would tend to dominate the misleading contour angle cue. For example, one could frame the contours with familiar objects, such as a road or a row of trees, which would tend to anchor the surface area to the ground.

Braunstein, M. L., and K. R. Stern. Static and dynamic factors in the perception of rotary motion. Perception and Psychophysics, 1980, 27, 313-320.

Key Words: Slant perception; interposition; occultation; illusory perception

Eighteen observers monocularly viewed slides of twelve plane outline forms through a circular aperture and provided static slant judgments by adjusting a plywood rectangle to the perceived slant of each of the forms. Four basic forms were used; all were subdivided by vertical lines. One basic form contained a vertical compression gradient by systematically altering the spacing between the vertical lines, and a horizontal perspective gradient by employing a trapezoidal shape. The second basic form employed a vertical gradient but not a horizontal gradient (by using a rectangular shape). The third basic form had a horizontal but not a vertical gradient; the fourth had neither a horizontal nor a vertical gradient. Eight additional forms were generated by overlapping the subparts of the forms such that the interposition of subparts was either in conflict or compatible with the gradient cues to slant.

Slant judgments were affected significantly by both gradients and interposition and were significantly lower for forms displaying conflicting interposition and vertical gradient information than for forms not displaying this conflicting information.

CIG Implications: These results caution that when surfaces are seen at a slant in CIG displays, the presence of false interposition information may create the illusion that the surface is flat (i.e., appearing in the frontoparallel plane). The converse may also occur. This illusion can only occur when the contours of features on the surface are overlapping. The elimination of apparent overlap of surface features in CIG displays will prevent the occurrence of this type of slant illusion.

Cross, J., and J. Cross. The misperception of rotary motion. Perception and Psychophysics, 1969, 5(2), 94-96.

Key Words: Rotary motion; depth perception; shadow; linear perspective; interposition

Two principles (shadow interposition and linear perspective) for predicting the relative frequency of illusory reversals of rotating plane objects were derived and tested empirically. Ten objects were used that variously combined valid and confounding depth cues. Both rectilinear and circular objects were used, and they were subdivided into five classes: 1) objects without confounding depth cues, 2) objects with shadow interposition cues, 3) objects with linear perspective cues, 4) objects with shadow interposition and perspective cues, and 5) objects in which shadow interposition cues were incompatible with perspective cues. The stimulus objects were mounted on a vertical shaft attached to a phonograph turntable and were viewed through a circular aperture. Subjects viewed each object in rotation for 1/2 min each and pressed a telegraph key for each apparent change in rotation direction. Shadowed and/or perspectived objects were more productive of illusory reversals than the comparable plain figures, with the combination of both confounding cues producing more illusory reversals than either cue alone. Perspective alone was more productive of the illusion than shadowing alone. However, when in conflict, shadow interposition cues seemed to take precedence over perspective cues.

CIG Implications: The illusion of direction of rotation is intimately related to misperceived slant. These results suggest that in CIG displays shading could interact with interposition to yield misperception of surface orientations. For example, darkened areas along the contours of runways or other objects could result in the misperception of a raised surface, the darkened area being perceived as a connected side of the runway or surface. If the darkened areas appear along both contours, the entire surface appears raised in depth. If the darkened area appears along one contour, the surface appears to be slanted in depth and away from the darkened edge. To avoid this illusion of orientation, darkened areas should not appear in CIG displays along surface contours.

Degelman, D., and R. R. Rosinski. Texture gradient registration and the development of slant perception. Journal of Experimental Child Psychology, 1976, 21, 339-348.

Key Words: Texture gradient; slant perception

The perception of slant was investigated by manipulating variability of texture element size (one measure of texture regularity). Subjects at four age levels judged the physical slant of surfaces with three levels of texture element size variability. The textured surfaces were composed of rows of black squares. Successive rows were staggered to reduce linear perspective cues. Texture surfaces were identical except that one condition used only one element size (regular texture), and the other two conditions used three and five different element sizes. The generating surface was constructed to hold textured surfaces at one of five slants; these surfaces were monocularly viewed through an aperture.

It has been shown that texture gradients unambiguously specify absolute slant of a surface relative to any arbitrary reference axis. In the case of irregular textures where element size varies, size averaging must be used to differentiate the gradient. Therefore, one might expect texture gradient differentiation to be more difficult, with the result that the error rates for slant judgments of irregular surfaces would be larger than those for regular surfaces. The results indicated that texture size variability did not have an effect on absolute error at any age level. Absolute error also decreased as the stimulus slant increased from the frontoparallel plane.

CIG Implications: These findings suggest that if regular textures composed of individual unaligned elements are used to enhance slant perception in CIG displays (all other things being equal), it is not critical that all texture elements be the same size--i.e., element size may vary over a surface with no loss in slant-perception accuracy. However, whether the individual squares used in this study provided perspective information is questionable because of their differential shape when at varying orientations. If linear perspective dominates size as a gradient cue to slant, then the null results could be artifactual.

The relationship between degree of slant and accuracy shows that severer slants are more accurately perceived than lesser slants. In a simulated landing approach where texture gradients are the primary cues to slant, the perception of the runway slant may improve with the approach, so that problems of differentiating runway slant may be severest at the beginning of the approach.

Epstein, W. Two factors in the perception of velocity at a distance. Perception and Psychophysics, 1978, 24(2), 105-114.

Key Words: Velocity perception; transposition effect

Six experiments on how the surrounding framework affects perceived velocity of movement were reported. Two computer displays were presented for comparison. The moving component of each display was a circular point of light projected onto the back of a translucent monitor screen. Standard displays were viewed at one of five distances and were always partially occluded by a cardboard frame at one of five dimensions. The comparison display was always seen at a distance of 1 m. Subjects were instructed to adjust the velocity of the point of light moving across the comparison display to match the velocity of the standard.

In experiment 1, velocity setting of the comparison circle decreased as the frame size dimensions on the standard display were increased, a result which replicated Brown's transposition of velocity effect. Brown discovered that if all the linear dimensions of a movement field are transposed (e.g., doubled), the velocity has to be transposed in approximately the same proportion in order to maintain equality of perceived velocity. Experiment 2 demonstrated that constancy of velocity was maintained when the standard display with a single frame size was set at different distances. Experiment 3 demonstrated that the frameworks of movement were not perceived as relative size cues to distance. Experiment 4 varied the distance of the standard display as in experiment 2, but the frame size was also varied such that the frame's angular size remained constant. The results were consistent with the idea that velocities of the displays are judged as equal only when the moving targets in the two fields traverse the same fraction of their respective retinal fields in the same time. Experiments 5 and 6 showed that only the immediately proximate frame needs to be taken into account in assessing effects on velocity.

CIG Implications: For the case of moving objects within a single frame, these results would argue that the perceived relative velocities of moving objects depend only on the relative rate of retinal image displacement. If the monitor frame is taken to be the immediately proximate frame in a CIG display, then objects which move across the screen at faster rates than other objects will have greater perceived velocities, regardless of the presence of cues to relative distance between the objects. These conclusions, however, will not apply to perception in actual flight, since monitor frames will be absent. The monitor frames would be a source of velocity misperception in simulated flight which would not occur in actual flight. Eliminating the monitor frames from view would obviously correct the problem. It is possible that the monitor frame will not always be taken as the immediately proximate frame. A mountain may frame a truck which is seen moving across it, or a building may frame a truck in the same manner. If the distal velocities are equal in the two cases, the truck will appear to move faster against the building, which is smaller. In situations like this, velocity perception in the cockpit and the simulator will operate similarly.

A note of caution must be offered. It is possible that the frame sizes functioned as relative size cues to distance in these experiments, despite the evidence of experiment 2. If relative size cues were operative, the conclusion that distance cues need not be considered in the perception of velocity must be withdrawn. Only further research can decide this issue.

Epstein, W., and S. Franklin. Some conditions of the effect of relative size on perceived relative distance. American Journal of Psychology, 1965, 78, 466-470.

Key Words: Relative size; distance perception

In the absence of other information, a difference between the visual angles subtended by two or more objects may be sufficient to produce a perception of depth. The objects appear to be separated in depth--their perceived relative distances correlated inversely with their relative visual angles; i.e., the object which subtends the largest visual angle appears nearest. These observations define the well-known distance cue called relative size.

Sixty observers viewed pairs of cardboard shapes on luminescent panels positioned at equal distances from the observer in an otherwise darkened room where traditional cues to distance were reduced. The shapes were squares or circles, or one of each. In the first experiment, the size ratio between the shapes was varied and the absolute size difference was held constant; in the second experiment, absolute size difference was varied and size ratio was constant. The observers positioned a marker on a 20-in. ruler to indicate the apparent separation in depth between the two shapes, and provided verbal estimates of relative distance. Relative size was an effective cue to relative distance. Size ratio rather than absolute size difference was the crucial measure in determining the effectiveness of relative size. Contrary to common belief, similarity of shape was not necessary to the effectiveness of relative size. Relative size influenced relative distance judgments when a square was paired with a circle, just as when the two shapes were similar.

CIG Implications: These results show that relative sizes of objects should be a strong cue to the relative distances between objects in CIG displays, where veridical cues to distance are at a minimum. This distance cue is also likely to be very pervasive in CIG displays since similarity of shape is apparently not required for cue effectiveness. This cue can often operate as a misleading cue to distance in CIG displays, when adjacent objects have different sizes. When size dimensions of objects can be varied, it would be preferable to use same-sized nearby objects because the relative size cue would then function as a veridical cue to relative distance between objects.

Farne, M. Brightness as an indicator to distance: relative brightness per se or contrast with the background? Perception, 1977, 6, 287-293.

Key Words: Brightness; contrast; distance perception

A black and a white target were displayed, in five different conditions, on five gray backgrounds having different degrees of brightness (from very bright to very dark). The results show that the target having the higher contrast with its background is perceived as the nearer. With the off-white background, e.g., the black target appears as the nearer to the observer. These results contradict the well-known concept that the brighter target should in any case be perceived as the nearer. The relationship with the common background, rather than between the two isolated targets, is the indicator to distance.

CIG Implications: These results pose a problem for distance perception in CIG displays. For example, two adjacent objects may have differential shading to facilitate object discrimination. However, depending on the shading of their common background, one object will always appear closer than the other. Differential brightnesses may even account for the occasional illusion that an object is floating when, in fact, that object was meant to be anchored to the surface. For this reason, adjacent objects having the same localization in depth should not be provided with differential shading in CIG displays, unless other considerations dictate it.

Ferris, S. H. Motion parallax and absolute distance. Journal of Experimental Psychology, 1972, 95(2), 258-263.

Key Words: Motion parallax; distance perception; texture

When a subject's eyes move with respect to the environment or the environment moves with respect to the subject's eyes, there is a differential angular velocity between the line of sight to a fixated object and the line of sight to any other object in the visual field. If the observer rotates his head about a vertical axis, objects more distant than the fixated object appear to move in the same direction as the head movement, at velocities that depend on the distances from the observer. Similarly, objects closer than the fixated object move at velocities that depend on their distances, but in the opposite direction. This cue to distance has been termed motion parallax.

Several previous studies established that motion parallax is a useful source of information for perceiving relative distance. The accuracy of estimating absolute distance based on monocular motion parallax was determined both before and after specific training which consisted of ten trials of feedback as to correct absolute distance. With the usual distance information eliminated, subjects held their heads about a vertical axis while judging the distance of stimuli placed 1.22 to 4.57 m away. Although distance perception was poor before training, head movement produced more accurate judgments than did head fixed. After only ten training trials, accurate judgments based on motion parallax were obtained. The advantage of motion parallax was most evident at the far distances. Results with a white background were as good as with a textured background when subjects were given direct information about motion parallax. Good results were also obtained for motion parallax relative to a near reference object that was 76.2 cm away. The results indicate that motion parallax can be useful for absolute distance perception.

CIG Implications: The usefulness of motion parallax as a cue to absolute distance may be more limited in CIG displays than it was in this study. Although distance perception by motion parallax was very accurate to distances up to 15 m, it is likely to be a much less salient cue for air-to-ground distances of surface objects. Previous research has also shown that motion parallax produced by visual field movement alone is less effective than motion parallax produced by active observer movement. Moreover, the present experiment used motion parallax produced by the latter, and the only source of motion parallax in CIG displays is the former. Therefore, although we cannot expect absolute distance perception to be as good in CIG displays as it was in this study, the results indicate that a short period of training under reduced distance-cue conditions via feedback of correct distance may enable observers to use the motion parallax cue more effectively in CIG displays to improve distance perception.

Gogel, W. C. The organization of perceived space, I. Perceptual interactions. Psychologische Forschung, 1973, 36, 195-221.

Key Words: Depth adjacency; equidistance principle; specific distance tendency; size perception; distance perception; slant perception

The equidistance tendency is the tendency for objects or parts of objects to appear at the same distance from the observer. The strength of this tendency is inversely related to the directional separation of the objects or parts. This effect is most evident when all the usual cues to distance are removed, and least evident when effective distance cues are present. As distance cues are increasingly removed or weakened, the contribution of the equidistance tendency to distance perception is increasingly obvious. If two objects (for example, a disc and rectangle) are placed at different distances from the observer and no stimulus cues to their distance are given, these objects will usually appear to be at the same distance. Because of this appearance, their perceived sizes, in agreement with the size-distance variance hypothesis, will be proportional to their retinal sizes. Thus, if the diameter of the disc is physically the same as the width of the rectangle, the perceived diameter of the disc will be twice the perceived width of the rectangle. Experiments have shown the equidistance tendency can reduce perceived relative distance expected from the relative size cue, and can even reduce perceived depth generated by the very effective cue of binocular disparity. The equidistance tendency operates more strongly in CIG displays because they contain fewer distance cues than does the visual world. The depth separation of objects that are in close proximity on the monitor will be reduced because of this tendency. The relative retinal sizes of surface objects will also play a larger role in determining perceived relative sizes of those objects. The equidistance tendency will contribute locally to the perceived flatness of the display.

The equidistance tendency applies to the perceived depth between parts of objects also. When a luminous irregularly shaped surface (slanted in depth with respect to the frontoparallel plane of the observer) is viewed in the dark without cues to distance, it will appear in the frontoparallel plane as a result of the tendency of all parts of the surface to appear equidistant. This may partly explain why a runway seen at a far distance in CIG displays often appears in the frontoparallel plane instead of slanted in depth. Because the texture gradient on the runway surface is not easily differentiated at far distances, the visible texture elements on the runway appear equidistant, resulting in the flat appearance of the runway.

The tendency for an object to appear at a particular constant distance whenever cues to distance are eliminated is called the specific distance tendency. In the absence of distance cues, objects will tend to appear at a near distance from the observer (approximately 2 or 3 m). Again, the specific distance tendency will have a modifying effect even when distance cues are present. Direct evidence for the specific distance tendency is found in experiments in which a monocularly observed luminous rectangle was presented above the floor of a long visual alley.

As a consequence of the more distant portions of the alley being directionally closer to the rectangle than are the nearer portions, the equidistance tendency resulted in the rectangle appearing toward the back of the alley. Following the simultaneous presentation of the alley and rectangle, the lights in the alley were turned off to eliminate the equidistance tendency and the rectangle was the only visible object. When presented to the same observers who had previously seen the rectangle and the alley together, the rectangle appeared at a nearer distance than it had previously. Also, the change in the apparent distance of the rectangle, from the distant position in the alley to a nearer position when presented in the dark, usually resulted in a decrease in its perceived size in agreement with the size-distance invariance hypothesis (but in disagreement with common sense).

CIG Implications: It follows that the tendency for the rectangle to appear at a near distance with the alley absent was a perceptual effect and not merely a "best bet" response to inadequate distance information. It also seems that this tendency can modify perceived distance in the presence of weak cues to distance. Again, the specific distance tendency will operate more strongly in CIG displays than in the real world. When information for distance is totally ambiguous in the display, objects will tend to appear at a near distance, and their sizes will appear smaller than they will when distance information is not ambiguous.

It cannot be concluded that distance ambiguity in CIG displays will cause objects to appear localized at 2 or 3 m from the observer. Such a perception would violate the observer's firm knowledge that the surface objects are being portrayed at greater distances. Instead, the specific distance tendency will trade off with assumed distance, and perceived distance and size will represent a compromise between the two tendencies. Even when distance cues are not ambiguous, the specific distance tendency will have a modifying effect, reducing perceived size and distance. The equidistance and specific distance tendencies cannot be eliminated since they are observer effects, but their strength in CIG displays and in the everyday visual world can be equated by upgrading distance information in CIG displays to a level comparable to that found in the visual world.

Gruber, H. E., and W. C. Clark. Perception of slanted surfaces. Perceptual and Motor Skills, 1956, 6, 97-106.

Key Words: Texture gradient; slant perception

College students observed a physical stimulus through an aperture at one of three orientations and at each of four distances. The stimulus surfaces were composed of white dots irregularly distributed on a black background. The diameters of the dots were 3 or 6 mm; the mean distances between centers were 8 or 16 mm. Thus, there were four surfaces which may be described as follows: large dots--coarse, large dots--fine, small dots--coarse, and small dots--fine. Observers were required to adjust a comparison rod until it appeared to be at the same slant as the stimulus surface.

The results concerning the texture variables were consistent across all viewing distances and seemed to indicate an interaction between unit size and unit density. Of the textures composed of large units, the coarser texture consistently produced the more veridical impressions of slant at each distance of observation. Of the textures composed of small units, the reverse was true; the finer texture consistently produced the more veridical impressions.

In a second experiment, unit size was held constant while unit distance was varied. Perceived slant was a U-shaped function of the proximity of texture units, with the intermediate texture resulting in the most veridical slant judgments. The results of both experiments are consistent with the idea that, for a given pattern of gradients of texture density, there is a family of inverted U-shaped curves relating perceived slant to proximity of the texture units that contains a different curve for each size of texture unit. To produce a differentiable texture gradient, the texture elements must be far enough apart not to appear fused. If too far apart, they will simply be seen as separate perceptual figures on a homogeneous, untextured ground. The optimal spacing will depend on unit size.

CIG Implications: If the above analysis is correct, the optimal size of texture elements for random textures employed in a CIG display will be determined by the packing density of texture elements on the surfaces. Conversely, if the element size is given, there is a unique density of elements that will optimize slant perception. It is not possible to specify a unique optimal texture element size and density, since these two variables interact with each other. It is, of course, possible that the set of optimal texture element sizes and densities will not result in the best transfer of training if these textures are not representative of textured surfaces seen from an aerial view.

Hess, E. H. Shadows and depth perception. Scientific American, 1961, 204, 138-148.

Key Words: Shadow; depth perception

Observers viewed through an aperture a picture of flagstones set in a bed of mortar and decided whether the stones appeared to protrude from or recede into the mortar. The picture could be rotated to any angle. When the picture was presented to the observer in any of several positions up to 90° to the left or right of upright, the illusion of relief occurred. If the picture was presented in positions that were beyond 90° to the left or right of upright, most observers saw the stones recede into the mortar. Most subjects assumed the picture was illuminated from above, although in reality it was illuminated from below. Their assumptions regarding the location of the light source were consistent with their judgments of apparent depth. In everyday experience, objects are ordinarily illuminated from above, and people learn to use the information provided by light and shadow to determine whether a surface is curved toward or away from them. A bulge in a surface usually casts a shadow below it, whereas a depression in a surface usually has a shadow inside its upper edge. When these relationships are reversed, depressions appear as raised surfaces and raised surfaces appear as depressions.

CIG Implications: The power of attached shadow as a cue to depth is evident from the stone-in-mortar experiment. If shadow information is not provided in a CIG display, observers will not have the information needed to perceive a curved surface as a hill or a valley, unless the outline can be seen against the clear sky. Obviously this is a serious deficit. If shadow information were provided in CIG displays, observers could be trained to use their knowledge of the location of the light source and attached shadow information to differentiate hills and valleys. This training would transfer to an actual flight situation.

Higashiyama, A. Perceived size and distance as a perceptual conflict between two processing modes. Perception and Psychophysics, 1977, 22(2), 206-211.

Key Words: Size perception; distance perception; binocular perception; monocular perception; relative size cue

Three differently sized squares made by cutting openings in pieces of cardboard and illuminated from behind were successively presented at the same physical distance under three observational conditions. The 160 observers viewed the squares binocularly and monocularly in a darkened visual alley, and binocularly in a fully illuminated alley having a floor that was a laterally striped pattern of red and white rectangles. Observers gave verbal absolute judgments of perceived size and perceived distance for each of the squares in all three observational conditions. The results showed that in the full-cue binocular viewing condition, a ratio of perceived absolute sizes is equal to that of the corresponding visual angles, with perceived distances appearing equal to each other. In the reduced-cue monocular viewing condition, an object of smaller perceived size is judged as farther away than one of larger perceived size, with the observers tending to assume that the two objects are the same object or are identically sized. The binocular viewing condition in the darkened visual alley produced results intermediate to the other two conditions.

CIG Implications: The results indicate that in CIG displays, where distance cues are reduced compared to natural viewing conditions, the relative size cue will tend to dominate relative distance perception. In actual flight, which is a full-cue situation, relative size may not function as an important cue to distance. It is not known whether these differences will be a source of negative transfer of training. The results also indicate that when cues to distance are ambiguous in CIG displays, observers may tend to perceive similarly shaped objects as identically sized.

Hochberg, J. Perception, I. Color and shape. In J. W. Kling and L. A. Riggs (eds.), Woodworth and Schlosberg's experimental psychology, Vol. 1: Sensation and perception, New York: Holt, Rinehart, and Winston, 1972.

Key Word: Figure-ground organization

When a scene is organized into figure and ground, the figure has shape but the ground is relatively shapeless. The figure usually tends to appear in front, and the ground seems to extend behind the figure's edge. Many factors determine how figures are recognized and, of the two areas, which will be the figure and which will be the ground. If many distinct elements appear in the same plane, elements near each other readily group to form contours, an effect known as the proximity cue. If regular textures are used to define flat surfaces in CIG displays, the texture elements will not be subject to this figure cue. If random textures are used over a flat surface, elements which are surreptitiously proximate will be organized as figures, resulting in a perceived rough surface with protruding areas. As a closed region is made smaller, it tends more strongly to be seen as a figure. Thus, as random textures increase in density and/or viewing distance, further figure-ground segregation becomes probable, and the surface will appear even less flat. In at least some kinds of patterns, alignment with the main axes of space (horizontal and vertical) seems to determine figure perception. Obliquely aligned patterns are less likely to be seen as figures. Patterns which have good continuation, i.e., which are not broken and discontinuous, are also more likely to be seen as figures. These two latter cues apply to regular textures. When seen at most orientations, texture elements will tend to align obliquely or will misalign with little continuation. Under these conditions the surface will appear flat. When seen in select orientations, the texture elements will align along the major axes, and figure-ground segregation will occur.

CIG Implications: In CIG displays, where orientation to surfaces is in flux, the perception of figures over regular textured surfaces will wax and wane as a function of orientation. Regions that are marked off by closed contours tend to be seen as a figure more than do those with open or incomplete contours. It is possible that the individual texture elements will be perceived as figures protruding from the ground if the elements have closed contours. Because elements tend to form groups according to their lightnesses, if texture elements appearing over a surface are of the same lightness, the surface is more likely to appear flat than if the texture elements vary in lightness. Finally, elements that move simultaneously in the same direction tend to form a single group. In CIG displays where surfaces are constantly in motion, the simultaneous movement of texture elements over a surface in a single direction will tend to counteract the cues to figure segregation which may be present, thus enhancing the perceived flatness of the surface.

Holmberg, L. The influence of color vision dimensions on the perception of distance. *Psychological Research Bulletin*, 1972, 12(6), 1-11.

Key Words: Brightness; saturation; hue; color; distance perception

A gray disc was moved on a track parallel to the subject's line of vision until its distance appeared equal to that of a fixed color plate at a distance of 1 m. Twelve color plates were used, representing all combinations of three hues (red, green, and blue), two saturations, and two lightnesses. A reliability measure was used to screen out subjects with less consistent performance in repeated measurements. There were no significant effects from hue. Colors with high lightness were seen as closer than those of low lightness. Colors with low saturation were seen as more distant than those with high saturation.

CIG Implications: The main effect of saturation is a laboratory equivalent to the well-known effect of aerial perspective or atmospheric attenuation. In the real world, more distant objects appear less saturated than do near objects. In CIG displays, saturation of objects should be a decreasing function of distance. If all objects in the display are equally saturated, the distances of far objects are likely to be underestimated relative to the real world.

Levine, N. P., and R. R. Rosinski. Distance perception under binocular and monocular viewing conditions. Perception and Psychophysics, 1976, 19(5), 460-465.

Key Words: Texture gradient; distance perception; monocular and binocular vision

College adults and children in the first, third, and fifth grades judged the absolute distance of a small irregular white target outlined in black in a binocular condition and in one of three monocular conditions: no texture, compression gradient consisting of alternating black and white horizontal stripes, and multiple gradient. The multiple gradients consisted of compression, perspective (created by adding vertical stripes that converged at the horizon), size (relative change in solid angle or area), and density (relative change in number of elements per constant angular extent). Targets appeared at one of six distances from the nearest reference stripe, ranging from 20 to 120 cm. Accuracy of distance judgments did not differ significantly between the multiple gradient and binocular conditions. Both resulted in significantly more accurate distance judgments than did the compression gradient information, even though the latter is geometrically equivalent to the other cues present in the multiple gradient condition. The absence of texture information caused the poorest performance, indicating that relative height in the visual field is ineffective as a cue to absolute distance.

CIG Implications: These results demonstrate the importance of regular texture gradients in providing cues to absolute distance in monocular visual displays such as those used for CIG. Although a compression gradient consisting only of parallel lines is not effective as a gradient cue to absolute distance, the addition of converging lines to indicate linear perspective makes distance perception in a monocular viewing situation as effective as that in binocular viewing. However, since converging lines rarely appear in naturalistic environments (with the notable exception of runways), it is possible that training on these gradient cues may not result in effective transfer to a binocular situation.

Mershon, D. H., and W. C. Gogel. Failure of familiar size to determine a metric for visually perceived distance. Perception and Psychophysics, 1975, 17(1), 101-106.

Key Words: Familiar size; distance perception

Using one's knowledge of the familiar sizes of objects to determine the apparent distances of those objects is known as the familiar size cue to distance. If effective, this cue might be one of the factors responsible for supplying the metric (scalar) characteristics of perceptions of spatial extent within a visual display that reduces other information concerning scalar extents to a minimum. Subjects monocularly observed through an aperture a rectangular room with a checkerboard floor and a white far wall that had two black square windows. Each window contained a transparency of either a postage stamp or a college catalog. The familiar objects were both of the same kind, and were of the same angular, but different assumed sizes. The two objects in each window were shown at either the same or an unequal distance from the observer. Judgments of object size, relative depth of the two objects, and absolute distance of the far wall were taken. If familiar size of the objects determined the metric of the room, the room should have been perceived to be about six times as large when the catalogs, rather than the stamps, were presented in the window. Clearly, rather than a change of this magnitude, little, if any, scalar change occurred when the different familiar objects were used.

CIG Implications: These results clearly demonstrate that the presence of a familiar object in a CIG display will not tend to establish a metric whereby the absolute distances of unfamiliar objects present in the CIG display can be determined. Rather, it seems that the familiar objects will have no effect on the apparent distances of the other objects. This result is disappointing because in CIG displays, where cues to absolute distance are at a minimum, the inclusion of familiar objects apparently will not improve the ambiguity of absolute distances of surface features.

Newman, C. V. Familiar and relative size cues and surface texture as determinants of relative distance judgments. Journal of Experimental Psychology, 1972, 96(1), 37-42.

Key Words: Texture gradient; familiar and relative size; distance perception

A series of experiments showed that familiar and relative size cues to distance, either separately or in combination, influenced relative distance judgments in which the subject attempted to position one object midway between two others. The two objects were placed at different physical distances from the subject on a plain white surface. The subjects viewed the objects through an aperture under reduced, monocular conditions. In the third and fourth experiments, a compression texture gradient consisting of alternating horizontal black and white stripes was used. In a previous study using an identical apparatus, this type of texture gradient was found to influence relative distance judgments. In the present study, relative size cues were found to influence bisection judgments, despite the fact that texture provides clear information about the objective position of the midpoint and is known to independently influence relative distance judgments. However, when familiar and relative size cues were held constant, relative distance judgments were influenced by variations in surface texture.

CIG Implications: A static monocular texture gradient is an ambiguous stimulus corresponding to a family of tridimensional arrangements of surface slant and spacing of the texture elements. Until this ambiguity is removed, the subject must make assumptions about texture spacing and slant. The present results show that other cues to distance, such as relative size and familiar size, can alter the assumptions made about texture gradients. They also confirm that a static monocular texture density gradient cannot unequivocally determine relative distance.

If a texture gradient of parallel horizontal lines is used in a CIG display to convey relative distance information, it should be supplemented with other distance cues to remove ambiguity. One method would be to include many familiar objects such as buildings, roads, and automobiles in the world model. The inclusion of many identically shaped objects with identical distal dimensions at different locations would make the relative size cue effective.

These findings cannot be generalized to other static monocular gradients, such as perspective gradients (converging lines), or to dynamic monocular gradients which appear in CIG displays and may more unambiguously define relative distance.

Newman, C. V., E. A. Whinham, and A. W. MacRae. The influence of texture on judgments of slant and relative distance in a picture with suggested depth. Perception and Psychophysics, 1973, 14(2), 280-284.

Key Words: Texture gradient; slant perception; distance perception

Six surfaces from natural environments with different visual textures were photographed at three different orientations. Beach pebbles, a concrete aggregate, and a grass lawn were exemplars of irregular texture; paving stones, a brick wall, and tiles represented regular texture. Subjects viewed slides of the surfaces and then made slant and distance bisection judgments of the stimuli. When making relative distance judgments, subjects were not permitted to count the number of rows of texture elements.

The regular and irregular textured surfaces yielded significantly different slant and relative distance judgments, with regular textures being judged more veridically, especially at representations of greater slant. With all surface textures, increases in angles of represented slant gave significantly greater impressions of slant and depth. For slant judgments, relative distances and angle of represented slant were consistently underestimated.

The fact that regular textures were superior to irregular textures with regard to slant and distance perception was probably due to the rectangularity of element shape and perspective gradients present only on regular textured surfaces. For slant and distance judgments, variations in linear perspective and element size between the regular textured surfaces had no effect. Within the group of irregular textured surfaces, slant judgments increased significantly as element size decreased. Relative distance judgments followed a similar but less consistent pattern. CIG Implications: We should be careful in applying the results from ecologically valid surface textures to artificially constructed surface textures used in CIG displays. This study contains potentially confounding variables such as brightness, saturation, and shadow; but since they were present in each stimulus condition it is reasonable to suppose that regular textures will yield better slant and relative distance perception than will irregular textures in CIG displays. This conclusion is consistent with previous research. For CIG displays, regular textures should also be preferred to irregular textures because they do not cause the annoying effect of element size on slant and distance judgments. Since regular textures occur less frequently than irregular textures do in the everyday visual world, they may lead to less effective transfer of training.

Oyama, T. Perceived size and perceived distance in stereoscopic vision and an analysis of their causal relations. Perception and Psychophysics, 1974, 16(1), 175-181.

Key Words: Convergence; visual angle; familiar size; distance perception; size perception; size-distance invariance; stereoscopic vision

Effects of visual angle and convergence upon the perceived sizes and perceived distances of a familiar object (playing card) and a non-representational object (blank white card) were investigated. Pairs of positive colored photographic transparencies of a playing card and blank white card were stereoscopically presented by two projectors with polarizing filters on a daylight screen located at one end of a dark visual alley. At the other end of the alley was a funnel-shaped viewing hood and an observation window. Accommodation was kept constant; convergence was varied by lateral displacement of one of the projected images. Six observers provided judgments of perceived height and perceived distance in centimeters after obtaining good stereoscopic fusion of each stimulus.

The results indicated that size estimates increased nearly proportionally as the visual angle increased, and decreased nearly linearly as the convergence increased. Distance estimates decreased nearly linearly as either the visual angle or the convergence increased. The ratio of the size estimate to the distance estimate for a given visual angle was almost constant irrespective of convergence. In this sense, the size-distance invariance hypothesis held. No clear effect of familiarity was found. Partial correlations were used to discriminate direct and indirect causal relationships between the stimulus variables and perceptual estimates. Both perceived size and perceived distance were found to be determined

directly by the two stimulus variables, but to be mutually related only indirectly. The causal analysis shows clearly that it is neither the case that perceived distance is calculated directly from perceived size nor the case that perceived size is calculated directly from perceived distance, at least with respect to the cues of convergence and visual angle.

CIG Implications: For CIG displays, it is erroneous to assume that the size of objects is given directly once perceived distance is established. Neither can it be assumed that if the size of objects is known, perceived object distance is determined. Rather, the perceived sizes and distances of objects in CIG displays are distinct matters and thus must be considered separately. This interpretation has a two-edged blade: it does not follow that if either perceived size or distance of an object is unambiguous, the other is also unambiguous. It may be the case, for example, that the distance of an object is ambiguous while the size of the same object is clear and unambiguous.

Phillips, R. J. Stationary visual texture and the estimation of slant angle. Quarterly Journal of Experimental Psychology, 1970, 22, 389-397.

Key Words: Texture gradient; slant perception

Eight pictures of slanting surfaces were constructed with the aid of a computer. These consisted only of texture elements; in this case outline circles and ellipses. The computer program generated pin-hole camera perspective pictures of a plane of randomly distributed equal circles viewed at different slant angles. Three factors were varied orthogonally to yield the eight stimulus pictures, and each picture was drawn at one of two levels of Gaussian noise. The size and shape of the ellipses were calculated to indicate a slant of 70° or 45°; the density distribution of the ellipses was also calculated to indicate a slant of 70° or 45°. Thus, for half of the pictures, size and density gradients specified a common slant; for the other half, size and density gradients were in conflict. Subjects studied all possible pairs of the eight pictures and indicated which had the greater tilt. Both size and density gradients were found to affect tilt judgments; however, when the two gradients were placed in conflict, a significant preference was found for the greater slant as determined by the shape and size gradient cue. Therefore, the shape and size gradient cue dominated the density gradient cue.

CIG Implications: If random textures composed of distinct elements are used in a CIG display, elements should be portrayed at differential sizes which correspond to the gradient appropriate to the slant at which the surface is seen. This type of random texture should yield more accurate slant perception than would a random texture of equal-sized elements which contains only density gradient information. In addition, a size and shape gradient of random texture elements more closely approximates natural viewing conditions, so that greater transfer of training can be expected.

Rogers, B., and M. Graham. Motion parallax as an independent cue for depth perception. Perception, 1979, 8, 125-134.

Key Words: Motion parallax; depth perception

The perspective transformations of the retinal image, produced by either the movement of an observer or the movement of objects in the visual world, were found to produce a reliable, consistent, and unambiguous impression of relative depth in the absence of all other cues to depth and distance. All observers also correctly identified all 12 three-dimensional forms of the stimulus patterns specified by the perspective transformations. The stimulus displays consisted of computer-generated random-dot patterns that could be transformed by each movement of the observer or the display oscilloscope to simulate the relative movement information produced by a three-dimensional surface. Using a stereoscopic matching task, the second experiment showed that the perceived depth from parallax transformations closely agrees with the degree of relative image displacement, and also produces a compelling impression of three-dimensionality not unlike that found with random-dot stereograms. Self-produced movement also resulted in greater impressions of depth than did externally produced parallax.

CIG Implications: Much previous research regarding the effectiveness of motion parallax is equivocal or even contradictory to the results of the present investigation. On the whole it seems that the clearest evidence for the effectiveness of motion parallax comes from those studies which have used complex or information-rich displays.

From these results it appears that motion parallax can function effectively to give reliable, unambiguous, and compelling impressions of depth in the surface features of CIG displays.

Rosinski, R. R., and N. P. Levine. Texture gradient effectiveness in
the perception of surface slant. Journal of Experimental Child
Psychology, 1976, 22, 261-271.

Key Words: Texture gradient; slant perception

To assess the relative effectiveness of different sources of information, college adults and children in the first, third, and fifth grades were asked to judge surface slant on the basis of monocular texture gradient information. Three types of stimuli were employed: one providing only compression gradient information (relative change in angular height); one providing only perspective gradient information (relative change in angular width); and one providing compression, perspective, size (relative change in solid angle or area), and density (relative change in number of texture elements per constant angular extent) gradient information. The stimuli were generated by the technique of polar projection shadow casting. A point source was projected through a transparent generating surface which could be set at different slants. The shadows were cast onto a frosted screen. Compression gradients were created by placing a horizontally striped piece of plexiglas over the generating surface; perspective gradients were created similarly with vertical stripes. All four gradient types are mathematically equivalent, but may be differentially effective in perception. Each group of subjects made slant judgments for only one of the stimulus conditions and viewed the textured surfaces at each of five slants through an aperture in a monocular viewing situation.

Absolute errors in the compression gradient condition were significantly greater than those in the perspective or multiple gradient conditions. Accuracy in the perspective and multiple gradient conditions did not differ significantly. Mean correlations between physical and judged slant for the stimulus condition's multiple gradients, perspective, and compression were 0.81, 0.72, and 0.28, respectively.

CIG Implications: These findings show that a gradient consisting of horizontal lines alone is an ineffective cue to slant. Moreover, horizontal lines do not enhance slant perception when converging vertical lines are present. The results indicate that if a regular texture gradient is used to facilitate slant perception in a monocular visual display, converging vertical lines are sufficient. However, it may be that training on this gradient cue will not lead to effective transfer in a naturalistic situation where regular texture gradients are scarce.

Sedgwick, A. The visible horizon: a potential source of visual information for the perception of size and distance. Dissertation Abstracts International, 1973, 34(3-B), 1301-1302.

Key Words: Size perception; distance perception; horizon

The visible horizon of the terrain is mathematically analyzed as a potential source of information for the perception of size and distance. It is shown that for an object standing on a flat ground surface of sufficiently great extent, the height of the object relative to the height of the point of observation is closely approximated by the ratio of the visual angle subtended vertically between the base of the object and the plane of the horizon. It is also shown that when the ground surface is of less than infinite extent, the use of this simple horizon ratio relation will produce an increasing overestimation of size with increasing distance. It is shown that the horizon provides a visual reference line against which the absolute sizes of objects are specified during parallax arising from motion or binocularity.

Observers were required to choose, from a series of pictures of pairs of rectangular objects standing on a flat, infinitely extended ground surface, the taller object in each pair. In one condition, the only stimulus information for size was the elevation of each object; in a second condition, the horizon line was added. In a third condition, a texture gradient was added to the pictured ground surface. A fourth condition was identical to the third except that the pictured ground surface was abruptly terminated at a large but finite distance, thus lowering the ground surface's visible horizon below its true mathematical horizon. The added horizon significantly improved relative size judgments, but the further addition of a texture gradient did not improve accuracy. A finite horizon resulted in size overestimation of the farther object. Apparently, the horizon ratio relation is used in size perception and can be a more salient cue than texture gradients.

CIG Implications: These results demonstrate that under some conditions very accurate size perception of surface features can occur in CIG displays, even when distance perception is totally ambiguous. This cue can be used to determine the height off the ground of surface objects if observer altitude is known. Or, perhaps, if object height is known, a perception of observer height may result. The necessary condition seems to be a clear perception of the object in relation to the horizon. It may especially aid in yielding veridical size perceptions of buildings in the vicinity of attempted landings.

Slocum, R. V., and W. A. Hershberger. Perceived orientation in depth from line-of-sight movement. Perception and Psychophysics, 1976, 19(2), 176-182.

Key Words: Texture gradient; motion perspective; slant perception

Twelve college students viewed computer-generated displays of a cross comprising two orthogonal dotted lines. The vertical arm of the simulated cross was always in the observer's frontal plane, but the randomly textured horizontal arm was in one of nine orientations relative to the line of sight. The interstices of the horizontal arm were random samples from a uniform population, producing a texture density gradient expressible as a gradient of probabilities of interstice sizes. Previous research shows that the retina is sensitive to such gradients. Observers judged the apparent in-depth orientation of the horizontal arm by positioning a horizontal bar mounted on a rotary potentiometer. Each observer viewed the simulated cross in each of three stimulus classes: 1) Motion, in which the simulated cross, in effect, moved toward the observer's vantage point and thus both increased the display's absolute size and steepened the texture gradient. 2) Magnification, in which the simulated cross, in effect, remained at a fixed projection distance while the display's size increased exactly as did the motion display. This condition allows the effect of changing angular size to be separated from the effect of changing angular texture gradients. 3) Static, in which both the projection distance and absolute size of the cross remained fixed. This condition allows the separation of the effect of static texture gradients from that of dynamic transformations of texture gradients.

The static texture density gradient mediated perceived orientation in depth. Further, when motion perspective was added to the static texture gradient, the impression of depth was enhanced, with the greatest enhancement obtaining at the near viewing distance and at steep angles. When dynamic magnification was added to the static texture gradient, the impression of depth was attenuated; this effect was interpreted as an illusory case of motion perspective.

CIG Implications: The results indicate that random texture gradients can be used as effective cues to the perception of slant in CIG displays. The effectiveness of random texture is attributable to the motion perspective offered by object movement. Random texture gradients will tend to be differentially effective depending on surface orientation and distance. For example, in a runway approach, the perception of slant should become more veridical as the approach draws nearer and should reach a maximum at the point of touchdown. Perception of runway slant at far distances may not be better than could be provided under static conditions, which is even worse than could be provided under binocular conditions.

Sundet, J. M. Effects of color on perceived depth: review of experiments and evaluation of theories. Scandinavian Journal of Psychology, 1978, 19, 133-143.

Key Words: Chromostereopsis; color stereoscopy; depth perception; color perception

It has long been known that the color of objects may affect their apparent distances. Thus, most people judge equidistant objects differing in color (e.g., red and blue) to be located at slightly different distances. This phenomenon is most pronounced with highly saturated colors and with objects lying near each other, preferably within 1-1/2° to 2°. A distinction must be drawn between monocular and binocular viewing, because the color distance effects sometimes disappear for the former.

An experiment was reviewed in which subjects judged the relative size and distance of differently colored objects under reduced-cue conditions by moving a comparison field to match the apparent distance (size) of a standard field. The judgments of relative size turned out to be closely related to those of relative distance. The red field was judged as largest and nearest, the blue field was judged as farthest and smallest, and the green field was judged as between both with respect to distance and size. These results were the same no matter which field was standard. Current explanations of the monocular color distance effect rely on the optical quality of the eye known as chromatic aberration, i.e., that the refraction indices of light rays are inversely related to their wavelengths. Due to chromatic aberration, short-wave light is more refracted in the eye's optical media than is long-wave light. Thus, equidistant sources of different color cannot simultaneously be in focus on the retina.

Chromatic aberration of the eye is the point of departure for all theories of binocular color-distance effects. The main theories assume that apparent distance differences are due to a slight disparity between differently colored retinal images.

In the most thorough investigation of color stereoscopy, subjects viewed color fields in a wooden box through a window. The background could be varied both in color and luminance and was 35 cm behind the color fields; otherwise, the box was painted flat black on the inside. The color fields were squares cut from paper printed in highly saturated colors. Subjects adjusted the fields until they appeared equidistant. Perceived relative depth between color fields increased with increasing spectral distances between the colors, an effect that became more pronounced with increasing observation distance. In another study, differently colored fields were illuminated from behind by a joint source. When illumination was high, long-wave colors were seen in front of the short-wave colors; e.g., a red field was seen in front of a green. When illumination was reduced, the red-in-front-of-green impression became less pronounced and finally reversed so that the green field was seen in front of the red.

A final study showed that pupillary size strongly affects relative distance of colors. When small pupils were induced in observers, red fields were seen in front of green fields; when large pupils were induced, the green field appeared in front of the red field.

CIG Implications: The distance and magnitude of color-distance effects depend on many variables relating to viewing conditions and observe differences. The important point for effective transfer of training is that color-distance effects in actual flight and in the simulator should be equated. At least three variables are critical: 1) the colors used in CIG displays should not be highly saturated because object colors do not appear highly saturated at the viewing distances commonly encountered in the cockpit; 2) the brightness of objects in CIG displays should be comparable to the general brightness of objects seen from the cockpit; and 3) the general level of illumination in the monitor area will determine pupillary size and therefore the character of the color-distance effects.

Walker, J. T. Visual texture as a factor in the apparent velocity of objective motion and motion aftereffects. Perception and Psychophysics, 1975, 18(2), 175-180.

Key Words: Texture; velocity perception

On being shown slides of rotating disks, college students were required to adjust the velocity of a comparison disk to the standard disk. The comparison disk consisted of two black and two white sectors. The standard disk was one of a graded series of random textures of black dots. Six random textures were employed which differed in their degree of coarseness. The coarsest (largest) texture in the series was ten times as coarse as the finest (smallest) texture. The standard disk was rotated at one of three velocities. The apparent velocity of the rotating random textured disk was found to be an increasing monotonic function of the coarseness of the texture. The range of texture used in the experiment produced a 25.6% change in the apparent velocity of the rotating disks.

These results ran counter to earlier findings. In these earlier studies, however, the moving textures were viewed through an aperture, so that the greater apparent velocity of finer textures could be explained on the basis of frequency of appearance and disappearance of texture elements at the edges of the viewing aperture. A viewing aperture was not used in the present study and, since every texture element was visible at all times, apparent velocity measures were free of any effects due to the appearance and disappearance of texture elements.

CIG Implications: The results indicate that the size or coarseness of texture elements may be critical to the observer's perception of his relative motion with respect to the textured surface over which he is moving. For example, if an observer is flying over a mountain range provided with random texture in a CIG display, the apparent velocity with respect to the surface will increase as the texture element coarseness increases. If the mountain texture seen during training is coarser on the average than that seen during actual flight, simulator training may result in velocity being underestimated during actual flight. Conversely, training on finer surface textures than are generally seen from an aerial view may result in velocity being overestimated during actual flight. Therefore, if surfaces are provided with random texture in CIG displays, the texture elements of surfaces should be the same average size as the elements of those surfaces as seen from an aerial view. The calibration of texture coarseness should yield maximum transfer of training with respect to relative velocity perception.

Yonas, A., L. T. Goldsmith, and J. L. Hallstrom. Development of sensitivity to information provided by cast shadows in pictures. Perception, 1978, 7, 333-341.

Key Words: Shadow; distance perception; size perception; shape perception

The shadow cast by an object in a two-dimensional picture can specify for the observer 1) the spatial relations between that object and its surroundings and 2) the shape and size of the object. Some sensitivity to this information is present even in 3-year-old children. Experiment 1 provided evidence that 3- and 4-year-old children can rely on the shape of the shadow cast by an object to judge the object's shape. When asked to judge the true shape of an ellipse drawn on the floor of a hallway that provided linear perspective and compression gradient information, they were more likely to choose the ellipse as a round figure when a shadow was continuously connected to it and thus specified that the object was resting on the floor than when either a shadow specified an object perpendicular to the horizontal surface or no shadow was present.

In experiment 2, adults and 3½ and 4-year-old children were shown displays consisting of pairs of pencil drawings. Each drawing presented a sphere on a linear perspective representation of a gridded ground surface which receded to the horizon. One type of display contained no shadows and only varied the object's vertical position in the picture plane. A second type of display presented the spheres in the same position on the picture plane, and only differed the location of the shadows cast by the spheres. The observers were to decide which sphere in each pair of drawings was higher off the ground, nearer, and larger. The location of the shadow cast by an object influenced the object's perceived relative depth and height off the ground plane.

CIG Implications: Although even the 3-year old children were sensitive to the location of the cast shadows, there was evidence that judgment of the object's relative distance and size improved with age. These results argue that cast shadows constitute an important source of information for determining the shapes and sizes of objects and for the layout of objects in space. In the case of CIG displays, cast shadows may also be helpful in determining the slant of objects. In addition, they may eliminate the illusion of floating objects because an object is necessarily resting on the ground if its ground shadow is attached to it. The cast shadow may also help determine the relative distance and height off the ground of other low-flying aircraft.

B.9 PERCEIVED FLATNESS OF THE DISPLAY

A pilot trainee viewing a CIG display is presented with a simulated three-dimensional environment via a two-dimensional display surface. These two perceptual interpretations of the display conflict with each other. The simulator features that reinforce the idea that one is watching a two-dimensional display are called flatness cues. The degree to which these cues can be eliminated from the display determines the upper bound upon how compelling the three-dimensional interpretation can be. The research treats perceived flatness of the CIG display and its effect on the perceived shape, slant, and size of surface objects, and the observer's relative motion and velocity with respect to the surface.

Epstein, W., and J. N. Park. Shape constancy: functional relationships and theoretical formulations. Psychological Bulletin, 1963, 60(3), 265-288.

Key Words: Shape constancy; shape-slant invariance; slant perception; monocular perception; binocular perception

When a form is projected by light on the retina, the differing orientations of the form with regard to the retina result in a set of different projective shapes. Under most conditions, phenomenal shape is less affected by the stimulus object's orientation with respect to the observer than would be expected on the basis of the projective transformations which accompany variations in orientation. The term "shape constancy" has been introduced to designate this fact. Shape constancy is usually defined as the relative constancy of the perceived shape of an object despite variations in its orientation. Several investigators have shown that shape constancy is diminished by conditions which reduce the availability or effectiveness of perceptual cues to an object's orientation. There is some evidence that the effect on shape judgment of eliminating binocular cues to distance will vary with the angle of inclination at which the standard stimulus is presented.

CIG Implications: In the everyday visual world, shape constancy is upheld because an abundance of binocular and monocular cues to slant are in evidence. Thus, pilots making a landing approach see the runway at its veridical slant and as rectangular in shape. In CIG displays, cues to distance (and slant) are more limited; furthermore, flatness cues exist that reduce the effectiveness of perceptual cues to the orientation of the runway. These flatness cues diminish shape constancy and cause the runway to appear trapezoidal and in the frontoparallel plane.

Rock, I., A. L. Hill and M. Fineman. Speed constancy as a function of size constancy. Perception and Psychophysics, 1968, 4(1), 37-40.

Key Words: Velocity perception; speed constancy; size constancy; binocular perception; monocular perception

If perceived velocity were to be a function of phenomenal extent traversed per unit of time, speed constancy would be derivable from size constancy, which entails employing distance cues. Experiments were performed in which observers matched the velocity of a luminous circle 72 in. from the eyes to the velocity of another luminous circle 18 in. from the eye in another direction. The two circles were of the same angular size. In one condition the displays were viewed binocularly to allow use of the cues of accommodation and convergence. In another condition, observers viewed the displays monocularly through an artificial pupil, thus eliminating distance cues. The results for binocular viewing show a strong tendency toward constancy of speed, based on the presence of cues to distance. For monocular viewing, the variable circle was set on the average 2.25 times the speed of the standard. Thus, when distance cues are eliminated, there is a tendency to regress toward matching the retinal velocities of the moving circles.

CIG Implications: In real-world perception where binocular cues to distance are available, velocity constancy occurs. An object seen at half the distance of a second object must possess twice the velocity of the second object for their velocities to be perceived as equal. However, in CIG displays where cues to distance are limited, there will be a greater tendency for objects to have equal perceived velocities if their retinal velocities are equal. Therefore, in comparison to real-world perception, velocities of distant moving objects will be underestimated relative to near moving objects in CIG displays. If, however, distance perception is improved by the addition of cues to distance such as texture gradients or shading, then velocity perception should improve accordingly.

Schlosberg, H. Stereoscopic depth from single pictures. American Journal of Psychology, 1941, 54, 601-605.

Key Words: Flatness cues; depth perception

An observer may see a picture either 1) as a picture representing depth or 2) as actual objects deployed in depth. Whereas in the first perceptual condition the observer remains aware of the picture's flat nature, under the second 'set' he gets the plastic (depth) effect. Depth, then, is not merely something added to a picture in various amounts, but rather a mode of perceiving. The impression of depth is an all-or-none affair. The plastic effect can be obtained almost as well by viewing a single picture through a lens as by the use of disparate pictures in a binocular stereoscope. The explanation for this effect lies in the fact that, while any picture may contain cues to depth, it also presents a number of cues for flatness.

CIG Implications: Identity of the binocular fields, surface glare, cues from accommodation, and margin of the picture are among the cues to flatness which are present in CIG displays. In normal binocular inspection of a picture, the flatness cues are strong enough to force the observer to see a flat picture; but, if the flatness cues can be eliminated or weakened, the perception can take on depth. As in the margin of a picture, the visible frame of a CIG display monitor is a cue to flatness. If the monitor frames can be covered so that they are not seen, this cue to flatness will be eliminated, thus permitting the depth cues in the display to become dominant enough to give the display an appearance of depth.

B.10 MINIMAL SCENE CONTENT

This research area treats the relationship between trainee acceptance and transfer of training and the CIG display's realism. For some aspects of the simulated environment, added realism may neither benefit nor reduce transfer of training. A lack of certain types of information in CIG displays may be compensated for by including a different type of information. For example, the lack of depth information caused by the absence of dynamic binocular disparity cues in CIG displays may be compensated for by providing artificial texture gradients without there being a concurrent loss in transfer of training.

Detection tasks required for actual flight may not be simulated with artificial clutter in CIG displays. A possible solution is a CIG display which switches level of detail based on eye movements; however, this display would have to keep up with the maximum velocity of saccadic and pursuit eye movements. Another criterion is whether the lack of detail in the periphery of the retina amounts to a noticeable difference to the observer.

Chase, W. D. Evaluation of several TV display system configurations for visual simulation of the landing approach. IEEE Trans. on Man-Machine Systems, 1970, 11(3), 140-149.

Key Words: Transfer of training; flight simulators; color perception

A study was conducted to determine the effects of several variations of two types of visual display systems on objective measures of performance and subjective evaluations. The components of the visual flight simulator were a television camera, runway model (scaled at 2000 ft = 1 ft), projector and monitor veiwing systems, and an instrumented fixed cockpit cab with engine sound and force-feel control systems. The visual scene was created from a runway model of an airport on a one-degree-of-freedom movable belt driven past the five-degrees-of-freedom camera and optical probe assembly. The subjects were seven professional pilots who were on professional flight status. Two types of flight approaches were made with either a projector or collimated monitor visual display: 1) the instrument approach and 2) the visual approach without the normal cockpit instrumentation assistance. The effects of color and reduced resolution were also examined. The touchdown distance and standard deviation for the color monitor display increased and agreed more favorably with actual flight results than did those for the black/white monitor display. The performance for rate of descent at touchdown was lower for color than for black/white (particularly with the monitor display) but was still higher than for actual flight. Degradation of the monitor display resolution tended to reduce the touchdown distance and slightly increased the corresponding standard deviation. In addition, the landings were made predominantly to the right of the center line for the black/white monitor display and with nearly twice the standard deviation as obtained for the color monitor display.

The pilots were more critical of the black and white variation for either display and favored more use of a color system. Advantages cited for a color system included greater pilot relaxation, decreased fatigue, better picture quality, and more realistic depth perception (particularly with the monitor display). Comparing the reduced-resolution monitor display to the projector display, the pilots also noted that the former caused a loss in depth perception and height references, increased visual fatigue, and increased efforts for a reasonable approach. The objective performance measures of the study were reasonably consistent with the pilots' subjective evaluations and comments.

CIG Implications: Even though the study was conducted with a simulator employing a physical model that is less sophisticated than current CIG systems, it demonstrates that lack of realism in the visual display can cause performance decrements even in experienced pilots. Of particular interest are the results regarding the use of color in the visual display. Considerations of cost effectiveness could lead one to regard color images as an unnecessary luxury in CIG displays, since a black/white display contains essentially the same perceptual information as does a color display. However, the results of this study indicate that reversion to a black/white CIG display would lead to decrements in pilot acceptance and flight proficiency.

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Hilz, R., and C. R. Cavonius. Functional organization of the peripheral retina: sensitivity to periodic stimuli. *Vision Research*, 1974, 14, 1333-1337.

Key Words: Peripheral vision; photopic vision; modulation sensitivity; spatial frequency

Previous research has shown that luminance-increment thresholds increase in the periphery; i.e., the amount of extra light needed to detect a change in brightness increases with the retinal eccentricity of the target. Sensitivity initially decreases as the test spot is moved a few degrees from the fovea; it then remains fairly constant to as far as 30° in the periphery, after which it again decreases monotonically.

In the present study, modulation sensitivity of the peripheral retina was measured for photopic vision with an interference fringe method that bypasses the optics of the eye and hence is not subject to optical aberrations. Light from a laser was divided into two beams and focused into two small focal images in the observer's pupil. The resulting interference pattern appeared to the observer as a vertical, red sine wave grating that filled a circular test field in a dark surround. Detection thresholds for the presence of bars in the interference pattern were measured by a method of adjustment in which the observer increased the contrast from below his detection threshold until the grating was just visible. For all spatial frequencies, sensitivity decreases with eccentricity, but the manner in which sensitivity varies with eccentricity depends on the spatial frequency of the test object. At 20 cycles/deg and higher, sensitivity decreases linearly and rapidly as eccentricity is increased; however, when measured with low frequency test objects, sensitivity remains rather constant until a certain eccentricity from 4° to 12° from the fovea (which depends on the spatial frequency) is reached, after which it decreases at the same rate as for high frequency test objects.

CIG Implications: If level-of-detail switching is employed in a CIG display, observers may not notice the lack of detail in the periphery if the level of detail decreases linearly at a certain rate as it becomes angularly displaced from the point of focus. This generalization may not hold for all surface features, however. Surfaces which are seen at low spatial frequencies at about 8 cycles/deg may be noticeably lacking in detail at eccentricities of up to 10° from the fovea, while surfaces seen at high spatial frequencies may appear normal with less representation of detail.

Hopkins, C. O. How much should you pay for that box? Human Factors, 1975, 17(6), 533-541.

Key Words: Transfer of training; flight simulators; cost effectiveness

Simulators may be used not only for training and maintaining proficiency, but also for predicting future success in training (selection) and evaluating the current effects of past training (proficiency assessment). A comprehensive, large-scale experiment was conducted in 1974 to determine how ground-based aircraft simulator motion conditions affect the prediction of pilot proficiency. For the best of the simulator motion conditions used, a correlation coefficient of 0.724 was obtained between measures of performance in a simulator and a corresponding light, twin-engine aircraft. These results support the idea that simulator performance tests can be used to evaluate the effects of past training.

The traditional measure of transfer of training--percent of transfer--is not adequate to evaluate the effectiveness of a simulator training program because it does not take into account the amount of simulator training. The real concern is with comparing the cost of a unit of simulator training time and the cost of flight time for which the unit of simulator training may be substituted. Eventually, an increment of simulator training would provide so little transfer that the flight time saved would thereby cost less than the next increment of simulator training. The use of the simulator beyond this point would not be cost effective.

CIG Implications: Many have questioned the necessity and desirability of universally high degrees of physical simulation, or the fidelity that may be achieved between the flight training device and the operational aircraft. In some instances, these training devices incorporate deliberate deviations from realism in attempts to improve upon, from the transfer-of-training standpoint, the relatively poor learning environment of the design-basis aircraft.

Many experienced pilots genuinely believe that the more a simulator responds and feels the way an airplane does, the greater its benefit to training and proficiency maintenance. Pilots love to fly. If they cannot fly in the air, they want to experience the closest thing to it on the ground. Fidelity of simulation can operate as a motivational variable. If the simulator looks, acts and sounds like an airplane, the trainee is more likely to be convinced that practice will be beneficial. The problem is to determine the extent to which varying degrees of fidelity of simulation yield varying degrees of motivation.

Johnson, C. A., and H. W. Leibowitz. Practice, refractive error, and feedback as factors influencing peripheral motion thresholds. *Perception and Psychophysics*, 1974, 15(2), 276-280.

Key Words: Peripheral vision; motion perception

The effect of practice on movement thresholds was determined at nine stimulus locations in the horizontal meridian, from 0° to 80° of eccentricity in 10° intervals. The subject was seated facing a perimeter with a 1.27-cm slit cut horizontally along its surface at eye level. Movement of the stimulus was accomplished by a 20.3-cm diameter cylinder covered with black paper and mounted with its long axis horizontal behind the slit opening. A 1.27-cm wide band of white plastic tape was wrapped in a single helix around the cylinder. Rotating the cylinder behind the slit produced horizontal movement of an approximately white test stimulus subtending 0.95° of visual angle. After each trial, subjects reported whether the stimulus had moved to the left, to the right, or remained stationary. An interleaved double staircase with variable step size was used to determine the movement thresholds, and a 50% correct criterion was selected as the threshold measure. By the final session, movement thresholds were 1.5 min of arc at the fovea, decreasing linearly to about 14 to 18 min of arc at 80° displacement from the fovea. Movement thresholds at 80° of eccentricity are only 10 to 15 times greater than at the fovea, while acuity is degraded by a factor of 200 or more over this interval. Not only is peripheral motion detection relatively better than acuity to begin with, but the amount of practice needed for optimal performance (three sessions) is apparently less than that needed for acuity (between 15 to 25 sessions).

CIG Implications: The results suggest that motion sensitivity rather than visual acuity should form the basis to establish the rate at which level-of-detail decreases with retinal eccentricity in CIG displays which possess switching capability. The level-of-detail should also decrease linearly as a function of eccentricity. If acuity thresholds are used to establish the level-of-detail rate of decrease, objects may seem to mysteriously appear and disappear as they are seen in motion on the display.

Mertens, H. W. Laboratory apparatus for studying visual space perception of the pilot in simulated night approaches to landing. Perceptual and Motor Skills, 1977, 45, 1331-1336.

Key Words: Transfer of training; depth perception; slant perception; realism

A laboratory apparatus is described that provides a relatively inexpensive way to assess many of the perceptual and human factors parameters in the night approach to landing. The basic concept of the apparatus was a moving runway model of variable slant. Added to this concept is a technique for modeling night runway lighting and an optical system for varying the model's position in the visual field. The runway model was based on a light box. Its removable Formica top was penetrated by short fiber optic strands to simulate runway lights. The sources were two parallel instant-start fluorescent tubes mounted below the top of the light box. One side of each fluorescent tube was covered with tape and painted black to make it opaque. The tubes were mounted with a single pin on each end so that they could be rotated to expose varying amounts of the unpainted sides in order to vary the amount of light reaching the optic strands and hence the brightness of the simulated runway and approach lights. The runway model with its rotation system was mounted on a cart that moved along a level track toward the observation position. A transverse horizontal axis of rotation, which was perpendicular to the longitudinal axis of the runway, passed through the plane of the simulated runway. The model could be rotated 20° from a physically horizontal orientation in either direction. The electromechanical and optical systems allowed precise control of simulated approach speed, model slant, and direction in the visual field of the simulated radial approach axis.

CIG Implications: The visual simulation apparatus has several important advantages. Optical resolution is excellent. The apparatus can vary the visual direction of the radial motion axis without needing a complex computer to synchronize simulated attitude and distance changes. The display's realism is enhanced by cues to space perception such as linear perspective and motion parallax, and by preservation of the natural relations of size and brightness of simulated runway lights to distance. Size and brightness gradients are not a feature of the runway lighting in CIG displays. The apparatus can be used to study the effects of the above cues on the perception of runway slant and approach angle. In addition, due to its enhanced realism, the apparatus can be used to inexpensively conduct on-the-ground transfer-of-training research with respect to such performance tasks as runway approach, landing, and takeoff.

Rock, I., J. Shallo and F. Schwartz. Pictorial depth and related constancy effects as a function of recognition. Perception, 1978, 7, 3-19.

Key Words: Depth perception; scene recognition; pictorial cues

It is argued that traditional pictorial cues to depth such as perspective or texture gradients are neither a necessary nor sufficient basis for recognition. That they are not necessary was shown by experiments in which stimuli were recognized as pictures of seascape and sky, but for which such cues were eliminated. Illusory size perception based on localization of objects in depth in such pictures nonetheless occurred. That they are not sufficient was shown by experiments in which photographs of grassy fields did not yield impressions of depth or related size illusions when conditions were such that the scene was not recognized (such as viewing the scene in non-upright orientations), even though the field contained size and density gradients and other cues to depth. Once recognized, however, these same pictures did yield impressions of depth. The results suggest that phenomenal depth based on pictorial cues, either in artificial visual displays or in real-life scenes, is not automatically produced by the various cues traditionally cited; instead, it is the end result of a construction process in which recognition plays a critical role.

CIG Implications: In real-world perception such as would occur when flying an aircraft, the impression of depth is facilitated by recognition of surface objects. Scene recognition even at high altitudes is easier than would be possible for CIG displays, since the level of detail is many times greater in the real world. Therefore, even if all the pictorial cues are present in a CIG display, their effectiveness in yielding depth impressions will be limited because scene recognition is poorer than in the real world.

There are two general ways to overcome this problem and thus equate CIG displays with the real world in terms of depth perception. The first method is to exaggerate the pictorial cues so that the perception of depth is compelling. Regular texture gradients might accomplish this purpose, but they suffer the disadvantage that, since they are rarely seen in the real world, they create a problem for transfer of training. A second method is to add cues that would facilitate scene recognition without necessarily increasing the level of detail. For example, a CIG display may employ individual texture elements to portray a field of crops. However, a random texture gradient thus created may not yield an unambiguous impression of orientation and depth if the field is not recognized as such, especially if the texture elements are neutral geometric shapes such as dots or squares. If the texture elements have a shape to suggest recognition of stalks of wheat or corn, for example, scene recognition becomes more probable. To facilitate recognition of an ocean surface, wavy lines could be used as texture elements. The main point is that in those cases where texture gradients do not seem sufficient to yield an impression of depth, if texture element shape can be tailored to surface identity, the improved scene recognition should lead to more veridical impressions of depth.

NOTE: The experiment of this does not use stereo imagery or motion as commonly used in human visual perception. Therefore, the conclusions are for a specific, limited case.

Valverde, H. H. A review of flight simulator transfer of training studies. Human Factors, 1973, 15(6), 510-523.

Key Words: Transfer of training; flight simulator

Studies conducted between 1949 and 1971 to statistically determine the transfer value of flight training simulators in use during that period are reviewed. Performance measures in these studies usually were instructor ratings of proficiency and errors during flight training. The various transfer-of-training studies have yielded equivocal results: some purported to find positive transfer as a result of flight simulator training, while others failed to find a positive effect of simulator training. This disparity may have been due to variables that were not assessed in the experiments. Most of the performance measures used in the experiments were judgmental in nature and thus highly subjective evaluation instruments. A need exists for more objective measures based on desired terminal behaviors. The value of paper-and-pencil aptitude tests to match subjects for a performance experiment is debatable. It must be assumed that there are individual differences in motor skills just as there are in any other human endeavor, and the low correlations obtained between paper-and-pencil tests and performance criteria seem to support this assumption. The motivation and attitude of the student toward the simulator may also affect his learning of the specified tasks.

Instructors play an extremely important role in transfer-of-training experiments; their biases, attitudes, motivation, etc., bear upon the learning situation. If they exhibit disdain for the trainer, the students will likely reflect this attitude. A capable instructor can provide the student with supplementary information to increase the trainer's effectiveness even though it has only minimal cues. Often the simulator instructor does not give instruction in the aircraft. For this reason, instructional techniques may vary widely between similator and aircraft training and thus adversely affect a transfer-of-training experiment.

Pilot training programs have used at least two variations in the instructional sequences for the simulator and the aircraft: alternating and block sequences. In the former, simulator training is alternated with actual flight training; in the latter, all simulator instruction is given prior to any training in the aircraft. After evaluating the studies which compared the relative effectiveness of alternating vs. block sequences, the evidence seems to favor the concept of block simulator instruction.

CIG Implications: The transfer-of-training studies conducted on flight simulators that are older and less sophisticated than those currently in use demonstrates the fact that simulators can yield positive transfer of training and that realism is not always necessary. To accurately determine the cost effectiveness of a particular flight simulator, it will be necessary to employ better experimental methods and more objective and valid measures than were used in the past.

Weisstein, N., and C. S. Harris. Visual detection of line segments: an object-superiority effect. Science, 1974, 186, 752-755.

Key Words: Visual detection; pattern recognition; feature detection

Subjects were shown a line segment in one of four orientations together with one of several context patterns. The subjects were required to determine which one of the four diagonal line segments was present in the briefly flashed display. None of the context patterns provided cues to which of the four target lines was present; in principle, a viewer could ignore the context and attend only to the target lines, without sacrificing accuracy. All five context patterns contained the same eight vertical and horizontal line segments--only their arrangement varied. The most unitary and three-dimensional pattern was one square overlapping another. The remaining four patterns were constructed to represent a graded tendency toward random arrangement of the line segments. The main finding was that when a target line was part of a configuration that looked unitary and three-dimensional, it was identified more accurately than when in any other context.

CIG Implications: The results have implications for the use of artificial clutter in CIG displays as a context for visual detection tasks. Artificial clutter should render detection more difficult than would a context such as a pictorial array of segregated objects that appear in depth. However, this does not mean that the use of artificial clutter will result in effective transfer of training. It may well be that the specific search and recognition procedures actually employed in a detection task will depend on the degree of organization of the context in which the target appears. Detection training with contexts which represent the everyday visual world in depth are likely to yield the most effective transfer. Of course, CIG displays lack the detail present in the everyday visual world, and this variable will also play a part in determining the effectiveness and difficulty of detection tasks.

Yarbus, A. L. Eye movement and vision. New York: Plenum Press, 1967.

Key Words: Eye movements; saccades

The frequency distribution of the amplitudes of small involuntary saccades arising during prolonged fixation on a stationary point was determined for a single subject. The amplitude of most such saccades lies between 1 and 25 min of angle. The minimal dimensions of these saccades are 2 to 5 min of angle, and the maximal dimensions are approximately 40 to 50 min of angle. Records show that the duration of the small involuntary saccades, depending on their amplitude, is 0.01 to 0.02 sec. If a CIG display capable of switching level of detail maintains a region of high detail covering 1° of angle or more at the point of fixation, then the observer will not be sensitive to changes in level of detail due to small involuntary saccades. The saccades will all remain within the region of highest detail.

The records of most horizontal and vertical saccades not exceeding 15° to 20° of angle very nearly approximate sinusoids. The angular velocity of a saccade while changing fixation points is given in degrees per second by

$$w = \frac{at}{2T} \sin \frac{\pi}{T} t \quad ,$$

where t is the time in seconds ($0 < t < T$), a is the amplitude of the saccade in degrees, and T is the duration of the saccade in seconds. It follows from this equation that the velocity of the saccade rises smoothly, reaches a maximum, and then falls smoothly to zero. For saccades smaller than 15° to 20°, the increase and decrease in velocity follow a sinusoidal rule. For large saccades, rectilinear areas appear in the middle part of the curve, and the time of increase in velocity of the saccade is shorter than the time of its decrease. The maximal velocities of the saccades increase as a function of their amplitude.

CIG Implications: For a saccade of 20° amplitude, the maximal velocity is approximately 450°/sec. The maximum amplitude of a saccade per frame in a CIG display, if 450°/sec is taken as a lower bound for maximal velocity, is 450/X, where X is the number of frames per second. For example, if a CIG display has a refresh rate of 60 frames/sec, a fast moving saccade may cover as much as 7.5° of angle per frame. If a region of high level of detail of 7.5° of angle or more is maintained, then the observer will not notice any lack of detail in the display. Faster refresh rates allow for smaller regions of high level of detail. Of course, these calculations may not hold for saccades that have amplitudes of more than 20° of angle.

NOTE: Saccadic suppression prior to, during, and after a saccade lowers perceived resolution for 0.05 to 0.1 sec.

B.11 SIZE AND CONTINUITY OF THE VISUAL FIELD

This research involves the visual factors that determine perceived self-motion and velocity of self-motion. Two key factors are the roles of peripheral vision and texture element size and density in self-motion perception.

In addition, the observer's sensitivity to discontinuities due to misalignment of monitors is discussed, and sensitivity to misalignment in the periphery of the retina and stimulus factors affecting vernier acuity (misalignment sensitivity) are treated.

Brandt, T., E. R. Wist, and J. Dichgans. Foreground and background in dynamic spatial orientation. Perception and Psychophysics, 1975, 17(5), 497-503.

Key Words: Self-motion; peripheral vision

The dependency of visually induced self-motion sensation on the density of moving contrasts as well as additional stationary contrasts in the foreground or background was investigated. Two different optokinetic stimuli were used: 1) a disk rotating in the frontoparallel plane and 2) a projection of horizontally moving stripes onto a cylindrical screen. The rotating disk induces an apparent body rotation in the opposite direction and causes a limited tilt of the apparent upright. The amount of this tilt can be measured in terms of the angle by which the test edge is displaced in the direction of the rotating stimulus so as to compensate for the perceived tilt in the opposite direction. The surface of the transparent rotating disk was randomly covered by varying densities of colored circles. A second stationary disk, also randomly textured with circles, was located behind the rotating disk. Similarly, in addition to the moving stripes on the cylindrical screen, a stationary pattern of vertical, opaque, black stripes could be affixed either in the foreground (in front of the screen) or in the background (in the plane of the projection screen). Circularvection latencies and velocities were measured.

It was found that 1) visually induced self-motion depends on the density of moving contrasts randomly distributed within the visual field and is saturated when about 30% of the visual field is moving, 2) additional stationary contrasts inhibit visually induced self-motion in proportion to

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their density, and 3) the location in depth of the stationary contrasts has a significant effect on this inhibition--the effect is considerable when they are located in the background of the moving stimuli but weak when they appear in the foreground.

CIG Implications: These results indicate that a minimum texture density is required for full locomotion to occur, perhaps as much as 30% of the CIG display area in peripheral regions. CIG displays that have fading detail at the periphery may not display enough information in those regions to induce self-motion. The monitor frames and other nonmoving parts of the simulator will also tend to inhibit self-motion, although not as much because they appear in the foreground.

Corwin, T. R., A. Moskowitz-Cook and M. A. Green. The oblique effect in a vernier acuity situation. Perception and Psychophysics, 1977, 21(5), 445-449.

Key Words: Oblique effect; vernier acuity

Observers viewed either vertical or obliquely oriented vernier targets from either an upright position or with their heads tilted. Vernier targets consisted of two misaligned line segments viewed through a circular aperture for brief periods in order to minimize the effects of eye movements. Performance was measured by an alternating method of limits with a three-alternative response. Vernier acuity was consistently better for retinally vertical than for gravitationally vertical targets, even when the targets were presented against a background context of vertical stripes designed to aid veridical perception of gravitational orientation.

CIG Implications: These results indicate that vernier acuity depends on retinal image orientation rather than on perceived orientation. When a contour of an object is continued from one monitor to an adjacent monitor, observers will be differentially sensitive to a misalignment of the contours between the two monitors, the critical factor being retinal orientation. If the observer's head is upright, sensitivity to misalignment will be greatest when the contour is horizontal or vertical. Misalignment of diagonal contours will be more difficult to detect. If the observer's head is tilted, maximum sensitivity to contour misalignment will occur when the contour is presented either at the same tilt as the observer's head or perpendicular to it.

Gogel, W. C. An indirect method of measuring perceived distance from familiar size. Perception and Psychophysics, 1976, 20(6), 419-429.

Key Words: Familiar size; distance perception

Two methods of measuring perceived distance as a function of familiar size were compared in five experiments. The method which uses the perception of motion accompanied by a motion of the head, unlike the method of verbal report, is considered to provide a measure of perceived distance that is unaffected by factors of cognitive distance. The amount of object displacement necessary for the object to appear stationary during head movement is the basis for the measure of perceived distance. When perceived and actual distances are equal, no object displacement is necessary for null movement perception during head movements.

The direction of object displacement relative to the direction of head movement necessary to stabilize apparent object position indicates whether perceived distance is an underestimation or overestimation of actual distance. Subjects viewed through an aperture luminous stimuli reproduced on transparencies in an otherwise darkened visual alley. A spherical lens placed all the stimuli accommodatively at optical infinity in order to reduce the effect of oculomotor cues of distance. The stimuli were a rectangle and three familiar objects: key, sunglasses, and guitar. The familiar size of the objects influenced perceived distance according to both measures. The guitar was consistently seen as more distant than the key. The familiar objects were often perceived as off-sized, with the key sometimes reported as larger than normal and the guitar usually reported as smaller than normal. Much larger variations in perceived distance due to familiar size were found in the verbal report measure than in the head movement measure. These results show that the effect of familiar size of objects on distance estimation is largely due to cognitive sources of information. The cognitive information is interpreted as resulting from perceiving the object as off-sized and assuming that an object's perceived size will vary inversely with its physical distance.

CIG Implications: Familiar size probably cannot be relied on as a cue to distance in CIG displays where there are relatively few cues to distance. Even if many familiar objects are included, they may be perceived as off-sized. The observer will be able to calculate veridical distances from his knowledge of the size of familiar objects and his cognitive assumptions concerning the relationship between size and distance; however, behavioral responses are more likely to be based on perceived distance than on distance estimates based on cognitive calculation. Perhaps training can help overcome nonveridical distance perceptions to allow responses during simulated flight to be based on distance calculations using familiar sizes of objects.

Johansson, G. Studies on visual perception of locomotion.
Perception, 1977, 6, 365-376.

Key Words: Linearvection; self-motion; peripheral vision; locomotion

The problem of a perceiver being able to visually determine whether he is seeing objects in motion or he is himself moving (locomotion) was addressed. Under rectilinear and smooth transport with constant speed, the only sensory information available about locomotion stems from vision. The apparatus comprised a video camera facing an endless moving belt that filled the screens of two video monitors with a vertically moving random pattern of black dots. The subject sat at a table with his head on a chinrest and with one monitor on each side of his head. The centers of the monitor screens were on his eye level, and each video screen covered a horizontal visual angle 45° to 90° from the optic axis of the eyes with the gaze directed straight forward. The apparatus was set up in a laboratory room that had plenty of furniture and equipment. The ceiling light was switched on during the experimental sessions.

A flow of vertical motion was presented to limited areas of the far periphery (45° to 90°) of the retina simultaneously with optical information about a stationary room over the rest of the retina. The result: most subjects perceived themselves as sitting in an elevator continuously moving up or down. Thus, peripheral motion stimulation over a few percent of the retinal area determines locomotion perception in apparent competition with information about a static state over the rest of the retina. The same type of stimulus presented to the central part of the retina always brought about perception of object motion and a static perceiver.

In a second experiment, the area of the retina exposed to motion stimulation was reduced to vertical bands that were 10° wide located on different parts of the retina. There was hardly any difference in the time required for locomotion perception to build up between different 10° peripheral areas in reaction to motion stimulation. Most subjects perceived locomotion when the vertical band was reduced to only 1° in width. Finally, in comparison to the open-laboratory situation, much better locomotion perception occurred when the central area in front of the eyes was screened.

CIG Implications: These demonstrations clearly show that monitors which stimulate the peripheral regions of the retina should be employed in flight simulators if perceptions of self-motion are desired. Apparently, only a very limited region of the peripheral retina need be stimulated in order to produce self-motion perception. Monitor wrap-around need not extend far into the periphery. If the peripheral retina is not stimulated by motion, the objects on the monitor will appear to be in motion, and observers will perceive themselves as stationary.

Kerr, J. L. Visual resolution in the periphery. Perception and Psychophysics, 1971, 9(3B), 375-378.

Key Words: Peripheral vision; visual acuity

Visual acuity thresholds were determined for two observers with a 3° square grating target presented for 0.2 sec within a steadily illuminated surround field matched in luminance to the test field. Measurements were made in the fovea, and at 10°, 20°, and 30° along the horizontal meridian of the temporal retina, at luminances between -3.5 and 3.0 log mL. The double staircase method was used to determine acuity thresholds. According to the observer's response of "Yes, I see the lines," or "No, I don't see lines," the grating line width was decreased or increased by adjusting the angular setting of the grating. The measure of visual acuity was the reciprocal of the visual angle subtended by the width of one line of the grating. At all retinal locations, the ability to resolve a grating increased with luminance. A large increase in acuity up to 1 or 2 log mL occurred in the fovea, but very little increase occurred above 0 log mL at peripheral locations. At photopic luminances, there was a sharp regular decline in log visual acuity as a function of retinal eccentricity, with no sign of leveling off at the most eccentric retinal location 30° from the fovea. The sharpest drop in acuity with eccentricity occurred between the fovea and 10° at 2.75 log mL. At scotopic luminances, retinal location had less of an effect, and at -3.25 log mL (close to absolute threshold), acuity changed very little with distance from fixation. Visual acuities were two to four times higher than those previously reported for the periphery. Despite this fact, it is evident that acuity drops sharply in the periphery.

CIG Implications: In a CIG display where the level of detail declines with distance from the fixation point, the lack of detail is not likely to be noticed by observers if the correct rate of attenuation of detail is used.

Lee, D. N., and J. R. Lishman. Visual proprioceptive control of stance. Journal of Human Movement Studies, 1975, 1, 87-95.

Key Words: Visual proprioception; mechanical proprioception; self-motion; locomotion

Maintaining a stance is an activity in which muscular corrections are continually being made on the basis of proprioceptive information about body sway. The two basic sources of proprioceptive information are mechanical and visual. Mechanical proprioceptive information could be obtained through the mechanoreceptors in the joints and muscles (particularly at the ankles), the soles of the feet, and the vestibular system. Visual proprioceptive information could be obtained through the changing optic array at the eye. The widely held view seems to be that if the eye is involved at all in balance, it is of minor importance compared to the mechanoreceptors and, in particular, the vestibular system.

The experiments were performed in a swinging room--a large box open at the bottom and one end. To provide more visual structure, lengths of floral wallpaper were hung on portions of the walls and ceiling. Two lightbulbs illuminated the room. The room was suspended 22 cm above the floor by four ropes to allow it to be swung silently and virtually linearly along its length. A sway meter detected the capacitance between the subject's back and a sensitive plate. Balance was tested at four stances: 1) standing normally, 2) standing on a ramp, 3) standing on a compliant surface, and 4) standing on toes. Testing was done both inside and outside the swinging room, eyes open and shut, and with the room stationary, moving sinusoidally, or moving irregularly. The subject was warned that the experimenter would try to make him sway by moving the room, and that the subject should do his best to resist swaying by ignoring the room movement while he still looked straight ahead. Visual proprioception was used in controlling balance in all four stances. The subject's body was visually driven by the sinusoidal motion of the room. Furthermore, when eyes were open and the room was moving sinusoidally, most subjects did not see the room moving. Visual proprioception improved balance in all four stances, being most effective in the more difficult ones. Misleading visual proprioceptive information could not be ignored. In all four stances, the irregular movements of the room caused visual driving and impaired balance. These results demonstrate that vision functions proprioceptively as an integral component of the control system for maintaining a stance. The experiments showed further that visual proprioceptive information is generally more sensitive than is mechanical proprioceptive information from the vestibular system and the ankles and feet.

CIG Implications: This study is a compelling demonstration of the dominant role of vision in self-motion perception. Not only is a moving visual environment necessary and sufficient for the perception of self-motion, but it seems to render proprioception of the vestibular system redundant. It seems probable that the illusion of self-motion generated by CIG displays can be as strong and compelling as that in actual flight, even though the latter also has vestibular input as a source of locomotion information.

Leibowitz, H. W., C. S. Rodemer, and J. Dichgans. The independence of dynamic spatial orientation from luminance and refractive error. Perception and Psychophysics, 1979, 25(2), 75-79.

Key Words: Circularvection; self-motion; luminance; refractive error

The effect of refractive error and luminance on circularvection--the illusory sensation of self-motion resulting from rotation of the visual field--was determined. Subjects were seated in the center of a rotatable drum whose interior surface was covered with vertical, alternating black and white stripes. When the drum was rotating with a velocity of 60°/sec, the subject was requested to open his eyes. First, drum motion is reported. After an onset latency of several seconds, this perception is followed by the sensation of simultaneous deceleration of the drum and a matching acceleration of self-motion. After a few more seconds, the drum appears to stop, and the subject perceives exclusive self-motion or vection in the direction opposite to drum rotation. After this stage, the subject is instructed to close his eyes, at which time he typically reports continued feelings of self-rotation, referred to as the aftereffect. The dependent variables consisted of the latency of these stages; i.e., the time to onset of circularvection, the time from onset to full circularvection, and the latency of the aftereffect. Circularvection was invariably experienced. Neither reduction of the luminance of the striped pattern to levels near absolute scotopic threshold nor the maximum induced refractive error of more than 16 diopters (resulting in blurred retinal images) abolished circularvection or influenced any of its latency measures.

CIG Implications: These results suggest that the luminance of CIG displays will not be critical in determining whether an observer will experience self-motion. Luminance levels need not be considered at all for this purpose. It also follows that differences in luminance levels between the flight simulator and actual flight will not lead to quantitative differences in degree or velocity of self-motion. The quality of image resolution also will not affect self-motion in the simulator.

Sullivan, G. D., K. Oatley, and N. S. Sutherland. Vernier acuity as affected by target length and separation. Perception and Psychophysics, 1972, 12(5), 438-444.

Key Word: Vernier acuity

The threshold for vernier acuity (sensitivity to misalignment of line segments) is about 2 sec of arc under optimal conditions. This sensitivity is very fine indeed, even much less than the diameter of a foveal cone. Vernier acuity was measured for vertical lines of different lengths; the threshold was almost as good for the shortest stimuli (squares, 1 min 20 sec) as for the longest (rectangles, 21 min 20 sec x 1 min 20 sec). For all subjects, the threshold was the same when a black horizontal separating line was present to fill the gap between the two rectangles and when the gap between the two rectangles was empty. The exception to this finding was that the threshold was elevated when a separating line was used with the shortest rectangles. When dots instead of rectangles were used as vernier targets, the threshold for the two dots, measured in terms of minimum detectable lateral offset, increased when the vertical separation between the dots increased. For one subject, the threshold linearly increased to a maximum of about 13 sec of arc for a dot separation of 20 min of arc; another subject's threshold attained about 17 sec of arc for a 10 min of arc separation. A final subject leveled at a threshold of about 10 sec of arc.

CIG Implications: The findings indicate that the length of the contours continued across monitors will not affect the observer's sensitivity to contour misalignment. However, for any contour length, observers will be able to detect the most miniscule misalignment between displays. This conclusion will be modified somewhat, depending on the spatial gap between the monitor displays. The greater the gap between the monitors, the less the sensitivity to misalignment. But even when large gaps are present, sensitivity to misalignment will still be very good.

Wist, E. R., H. C. Diener, J. Dichgans, and T. Brandt. Perceived distance and the perceived speed of self-motion: linear vs. angular velocity? _Perception and Psychophysics_, 1975, 17(6), 549-554.

Key Words: Circularvection; self-motion; velocity perception; distance perception

An experiment was performed in which subjects sat in an upholstered chair fitted with a head support so that the distance of the eyes from a cylindrical screen was equal to the screen's radius of curvature. An optokinetic simulator projected a regular moving pattern of black and white stripes onto the screen. One of two filter densities covered one eye in order to vary perceived absolute distance of the moving stimulus from the subject. Two stripe velocities were employed. The perceived distance of the moving stripes and the subjective speed of self-motion were determined by means of a magnitude estimation technique. Upon exposure to a given optokinetic stimulus, the subjects typically experienced object-referred motion for several seconds, followed by a brief period of mixed self- and object-referred motion. The subjects experienced a pure self-referred motion after about 5 sec, after which they made their magnitude estimates. Although perceived speed of rotary self-motion increased with the angular speed of the surround, it was also found that with the angular speed of the visual surround held constant, the perceived speed of rotary self-motion increased linearly with increasing perceived distance of the surround.

CIG Implications: These findings highlight the importance of adequate cues to absolute distance in producing impressions of self-motion in simulators that use CIG displays. If cues to distance are ambiguous or reduced compared to those in the everyday visual world, independent evidence suggests that distance underestimation relative to real-world distance perception will result. A consequence of this fact is that the perceived speed of self-motion will be less in the simulator than in the actual cockpit environment.

B.12 HYBRID DISPLAY AND UPDATE

In many CIG displays, the runway lights and other calligraphic representations overlaid on the raster format appear as multiple images. The explanation for this multiple-image phenomenon is discussed in the following summaries.

Braunstein, M. L., and O. F. Coleman. Perception of temporal patterns as spatial patterns during apparent movement. *Proc. of the 74th Annual Convention of the American Psychological Association*, 1966, 69-70.

Key Words: Flicker fusion; apparent movement; multiple-imaging effect

The multiple-imaging effect was demonstrated in an experiment which used three different 96-frame 8-mm film sequences displayed at 54 frames/sec. The sequences showed a white dot against a dark background. After every third frame, the dot's position was changed by an amount equal to eight times its diameter. In Type I the dot appeared, before each position change, on the first frame but not on the second or third frames; in Type II the dot appeared in the same position on the first and second frame, but did not appear on the third frame; in Type III the dot appeared in the same position on three successive frames. All observers reported seeing clusters of one, two, and three dots in apparent motion to sequences of Types I, II, and III, respectively. All observers reported the dot separation as equal to or less than the width of the individual dots. In a second experiment it was shown by using differently colored dots that the perceived spatial order of the multiple images corresponds to their temporal order of presentation. Finally, an increase in the time interval between two presentations of a dot in the same position resulted in an increased apparent separation between the dots within a cluster.

CIG Implications: The results clearly demonstrate that the problem of multiple images of runway lights which occurs in some CIG displays is caused by the update rate being slower than the refresh rate. The smaller the update-rate/refresh-rate ratio, the more serious the problem in terms of the number of multiple images. An increase in the refresh rate without a concomitant increase in update rate should reduce blur by decreasing the spatial separation of the images, but will not eliminate the problem. The problem can only be eliminated by increasing the update rate so that it is equal to the refresh rate.

Burr, D. C. Acuity for apparent vernier offset. *Vision Research*, 1979, 19, 835-837.

Key Words: Apparent movement; flicker fusion; multiple-imaging effect; vernier acuity

Observers viewed an apparently moving vertical bar, displayed sequentially for 50 msec periods at a series of discrete positions at 25 msec intervals between successive stations on an oscilloscope face. Under these conditions, the vertical bar appears to move past stations and across the spaces between them, simulating real motion. When the plotting sequence was such that the upper half of the bar was always displayed slightly before the lower (10 msec), the bar appeared to be broken and offset at the middle, with the upper segment leading the lower (although they were actually displayed at identical horizontal positions). To measure acuity for detecting vernier offsets produced in this way, a forced choice paradigm was used in which observers were required to identify the direction of the apparent offset of top to bottom segment. The segment pairs were again displayed at the same position with varying temporal offsets. Using the criterion of 75% correct identification, acuity for the two observers for temporal offset was 11 and 12.8 sec of arc. The temporal delays corresponding to the minimum detectable apparent offset were 1.9 and 2.2 msec.

CIG Implications: The conditions of this experiment are comparable to those in CIG displays in which the update rate is slower than the refresh rate. In the latter, the effect is seen as multiple images of runway lights. Other research indicates that the problem may be minimized by increasing the refresh rate without increasing the update rate, which results in a smaller spatial separation between multiple images. This study shows that, in the case of line segments, multiple images would remain detectable for refresh rates of up to 500 frames/sec. Thus, increasing only the refresh rate will not alleviate the problem.

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